

The Impact of Leachate from Clean Coal Technology Waste on the Stability of Clay and Synthetic Liners

Topical Report
March 1, 1995 - March 31, 1996

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Work Performed Under Contract No.: DE-FC21-93MC30127

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ACKNOWLEDGMENTS

This report was prepared with the support of the U.S. Department of Energy, (DOE) Morgantown Energy Technology Center, under Cooperative Agreement No. DE-FC21-93MC30127 and the Public Service Company of Colorado. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE or the Public Service Company of Colorado.

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EXECUTIVE SUMMARY

This project was developed to provide design criteria for landfill disposal sites used for sludges such as those generated using the Clean Coal Technologies (CCT) tested at the Public Service Company of Colorado's Arapahoe Power Plant. The CCT wastes used were produced at the Arapahoe Plant Unit No. 4, which was equipped with the integrated dry NO_x/SO_2 emissions control system installed under the Clean Coal Technology Program. The investigation emphasized the potential impact of clean coal technology materials (sodium and calcium injection systems and urea injection) on the permeability and stability characteristics of clay liner materials and the stability of synthetic liner materials.

Flexible-wall permeameters were used to determine the hydraulic conductivities (HC) of the clay liner materials affected by various compactive conditions. Tests were conducted using the waste materials overlying the clay liner materials through wet/dry cycles, freeze/thaw cycles, and over 120-day periods.

The impact of CCT materials on the characteristics of the clay liner materials studied in this project was minimal. The HC measurements of the waste/clay liner systems were similar to those of the water/clay liner systems. HC decreased for clay liners compacted at moisture levels slightly higher than optimum (standard Procter) and increased for liners compacted at moisture levels lower than optimum (standard Procter). Although some swelling was evident in the sodium materials, the sludge materials did not have a negative impact on the integrity of the liners over 120-day tests. Wet/dry cycles tended to result in lower HC, while freeze/thaw cycles substantially increased HC for the liners tested.

Tests were also conducted to assess the compatibility of synthetic liner materials with the CCT by-products. The test program was conducted using methods specified and/or referenced in EPA, SW 846-Method 9090 with some modifications. Compatibility evaluations were made using high-density polyethylene (HDPE), very low density polyethylene (VDPE), and polyvinyl chloride (PVC) synthetic liner materials treated with baseline fly ash materials (no CCT used), sodium injection materials, calcium injection materials, and materials generated from the sodium injection/urea injection/low NO_x burner control system. The synthetic liner materials were subjected to a 50:50 ratio of sludge to water for periods to 120 days at room temperature (23°C). At the end of each equilibration period, the liner materials were tested using mechanical engineering techniques and weight losses due to volatiles and extractables.

Sustained incremental changes in the measured physical properties of the materials over time were not observed. Some abrupt changes in strength were found several times during the testing period. However, these aberrations seemed more indicative of isolated changes in the conditioning methods or test procedures and could be related to flaws or changes in the materials related to manufacturing conditions. After 120 days of conditioning, none of the measured

physical properties varied significantly from those of the untreated liner materials. This was true for all samples regardless of the conditioning solution used.

The volatiles and extractables tests for the HDPE and VDPE materials indicated that the waste materials had little influence on their overall structure. However, the extractables data suggest that PVC liner material might decompose in the waste environments evaluated. The PVC liner material reacted similarly for all treatments with about a 30% weight loss.

INTRODUCTION

Landfills commonly used for disposal of solid wastes pose a threat to surface and groundwater quality. The major concern is that the leachates from the waste may contain elements that are detrimental to the quality of the waters for their designated uses. Clay liners are usually used in landfills often in combination with synthetic liner materials to prevent the movement of leachate from the disposal site. It is important to determine the compatibility of both the clay liner material and the synthetic liner material to the specific waste prior to prescribing a suitable liner system for a specific application.

Clay liners are often used in landfills to contain and attenuate the leachate from solid waste materials. The suitability of soil materials for liner use is usually based on permeability criteria (Brown and Anderson, 1980). However, other considerations relative to chemical-physical relationships often determine whether a clay liner is compatible with a specific type of waste. These relationships must be evaluated in detail before an appropriate liner can be prescribed for a specific landfill.

Problems often found with clay liners are related to volume shrinkage's (Hettiaratchi et al., 1988). Shrinkages in compacted liners often result from increases in salt concentrations in the solutions within the clay liner. Also, the impact of acidic and alkaline solutions on the dissolution of the clay minerals present in the clay liner materials results in increased permeabilities for similar reasons. The presence of certain organic compounds in the leachates are sometimes associated with increased permeabilities.

There are a number of variables that determine the effect of waste leachate on the long-term stability of a clay liner material. The primary variables include clay mineralogy, texture, surface chemistry considerations, the physical nature of the materials, and the chemistry of the waste leachate. Increases in salt concentrations can result in double layer collapse or less interaction between clay particles and resulting decreases in repulsive forces. A decrease in repulsive forces causes the materials to flocculate, reducing the effective stress in the liner, which results in a volume shrinkage. The mineralogy of the clay and the specific elements present in the solution associated with the clay will determine the amount of shrinkage that will result from double layer collapse. The 2:1 layer clay minerals such as montmorillonite have a much greater tendency for swelling and shrinking than the 1:1 clay types such as kaolinite. In addition, monovalent elements such as sodium that have a very large hydrated radius have the potential to cause swelling, while divalent elements such as calcium have a tendency to reduce double layer expansion. Therefore, materials that have high-swelling montmorillonite clay minerals with sodium as the dominant element should be avoided. Elements such as calcium can displace the sodium and cause the double layers to collapse. This type of reaction resulted in a large amount of shrinkage in studies done by Hettiaratchi et al. (1988) with permeant solutions containing calcium. These authors suggested that clay liner materials should be conditioned with calcium

solutions during the compaction stage to prevent shrinkage and cracking due to double layer collapse. However, it should be noted that if the salt concentration is increased to high levels (high electrical conductivity or EC) due to leachate migrating into the clay liner, no matter which cation is present, double layer collapse could occur, resulting in the formation of cracks.

Shrinkage of clay liners can also be caused by the influence of organic compounds on the electrical double layer. The low dielectric constant of organic compounds relative to water reduces the influence of the surface charge, promoting flocculation of clay particles causing cracking of clay liners (Green et al., 1983). However, the amount of organic compound seems to determine the degree of impact that the clay liners experience. Daniel et al. (1988) found that solutions containing low levels of organic compound did not cause shrinkage of clay liner materials. Therefore, it is apparent that most situations will require testing for compatibility between the specific wastes and the clay liner material to be used at the disposal site.

The load on the clay liner associated with the waste will also impact the effective stress experienced by the clay liner. Changes in effective stress with time may be an important factor in the long-term stability of a clay liner.

The use of flexible membrane liner materials to line waste disposal sites has been shown to be very effective in reducing leakage of contaminated solutions from the sites. Such membranes are used in numerous waste disposal applications, including the storage of fly ash materials in landfills. As technologies are developed to control air contaminant emissions from power plants, fly ash/sludge materials are produced that have characteristics much different from those of conventional fly ash materials. It is important to develop an understanding of the compatibility of the new sludge materials with the flexible liner materials used at the disposal sites. It is also important to understand that sludge materials are unique. Each power plant operates under different combustion conditions, a variety of coal qualities, and using different emission control systems; therefore, the character of the fly ash/sludge materials will differ. This requires that liner compatibility evaluations be made for each waste and/or waste leachate that is produced.

Flexible membrane liner compatibility studies have been conducted using clean coal technology (CCT) wastes by Koegler et al. (1991). These tests were done using fly ash/sludge materials that were generated from a number of power plants representing desulfurization technologies such as spray dryer, atmospheric fluidized bed combustors (AFBC), limestone injection and sodium injection. These researchers looked at 20 synthetic membrane liners of various types from different vendors. The findings indicated that water slurries of the wastes tested are chemically incompatible with some of the synthetic membrane liners tested. They also found that variations between synthetic liners of the same type, but obtained from different vendors, were significant. Therefore, it is recommended that before a liner is selected for a specific installation, compatibility tests using the actual waste material and liner samples from specific vendors should be completed.

OBJECTIVE

The purpose of this research was to investigate the potential impact of clean coal technology solid wastes on the permeability and attenuation characteristics of clay liner materials and on the integrity of synthetic membranes.

EXPERIMENTAL PLAN

The test program included three clay liner materials representing different overall characteristics. The liner materials represent two landfill sites in Colorado and one site being used in California. Four waste materials generated at the Arapahoe Power Plant during the Clean Coal Technology testing program were used in the testing. The CCT materials used in this study include: materials collected during baseline operations without the applications of the CCT; the sodium injection materials; the calcium injection materials; and the materials generated from the sodium/urea injection/low NO_x control system. This report will address the general aspects of the research findings.

Flexible-wall permeameters were used to determine the hydraulic conductivities (HC) of the clay liner materials affected by various compactive conditions, confining pressures, gradients, effective stresses and solution chemistry conditions. In addition, tests were conducted using the waste materials overlying the clay liner materials under wet/dry cycles, freeze/thaw cycles, and over long time periods. Dry cycles were conducted by allowing the liner materials to air dry to a point near field capacity (-1/3 bar matric potential) and did not represent an oven-dry condition.

Clay liner and fly ash materials were tested using compacted cylinders, 6 in. long and 4 in. in diameter. The tests were conducted at densities based on moisture/density relationships as described in ASTM D698. Clay liner material/fly ash simulations were done using 2 in. of clay liner material overlain by 2 in. of fly ash materials. The hydraulic conductivities of the various materials were determined using ASTM D5084-90.

The test program included compatibility evaluations for three types of synthetic liner materials including: (1) high-density polyethylene (HDPE); (2) very low density polyethylene (VDPE); and (3) polyvinyl chloride (PVC). The synthetic liners were immersed in the leachate environment associated with four waste materials generated at the Arapahoe Power Plant during the CCT testing program as noted previously. The synthetic liners were subjected to the fly ash materials for periods of 30, 60, 90, and 120 days. The 50:50 ratio of sludge to water used in this study deviates from the EPA Method 9090 which requires a 5 to 15% solids solution. This procedure was modified because the pH values associated with the dilute system specified in Method 9090 were 2 pH units lower than the pH of the 50% solids solution. In addition, the pH of the 50% solution compared well to the pH of the saturated pastes of the sludge materials used

in the study. The studies were done at room temperature (23°C). Comparisons of the synthetic material's physical properties, measured before and after contact with the leachates from the fly ash materials, were used to evaluate the compatibility of the liner with the waste over time. Testing included physical tests, tensile strength properties, and changes in volatile and extractable components of the materials.

The mechanical testing was performed using the guidelines of EPA Method 9090 with the exception of the puncture test, which was done using ASTM D4833. As directed by EPA Method 9090, the tensile properties method was specified as ASTM D638. The modulus of elasticity was measured for the HDPE and VDPE materials using ASTM D882, Method A. Tear strength was measured using ASTM D1004. The punch strength test method used was specified in ASTM D4833. The change in volatile and extractable weights presented on a percentage basis was done using methods specified in SW 870 Appendix III-D and Appendix III-E. Volatile losses provide indications of the amount of water absorbed into the liner. Large amounts of absorption show a degradation of the liner. A decrease in liner extractions as compared to the material before testing provides an indication of the components leached from the liner during exposure to a waste.

RESULTS

Clay Liner Material Evaluations

In general, the hydraulic conductivity characteristics found in this study were similar to those found by Daniel et al. (1988). As shown in Table 1, the hydraulic conductivity (HC) measurements decreased for clay liners compacted at moisture levels slightly higher than optimum (standard Procter) and increased for liners compacted at moisture levels lower than optimum (standard Procter) using tapwater as the permanent liquid. The waste/clay liner system reacted very similarly to the water/clay liner systems in terms of HC measurements. Although some swelling was evident in the sodium waste materials, the sludge materials did not have a negative impact on the integrity of the liners over the 120-day tests (Figure 1).

Table 1. Hydraulic Conductivity Evaluations for the PSC Natural Liner Material Under Various Water/Density Conditions with Tapwater as the Permanent Liquid

	<u>cm/s</u>
H.C. at STD Dry	2.0E-05
H.C. at STD Opt.	4.0E-09
H.C. at STD Wet	2.0E-09
H.C. at MOD Dry	2.0E-08
H.C. at MOD Opt.	7.5E-09
H.C. at MOD Wet	1.3E-09

Some initial dispersion of clays resulting in plugging of pores may be responsible for the gradual reduction in HC. Swelling and shrinkage due to the high sodium or sodic condition followed by the impact of high salt concentrations on the electronic double layer did not occur. This clay chemistry phenomenon was expected to have a negative impact on the integrity of the clay liner materials. The HC values for the 120-day test of the clay liner materials contacted with calcium injection waste are presented in Figure 2. Shrinkage of the clay liner materials due to high electrical conductivity levels was expected to cause cracking of the clay liner. However, cracking was not apparent, and the HC values stabilized within several weeks, indicating that the clay liner remained stable.

Wet/dry cycles did not have a major impact on the HC of the clay liner materials with time. The impact of wet/dry cycles on the system with sodium-injection fly ash overlaying a clay liner is shown in Figure 3. The decline of HC values with time closely resemble the trend shown in Figure 1 for a liner not impacted with wet/dry cycles.

The influence of freeze/thaw cycles on the HC values of a clay liner impacted with a calcium injection fly ash is shown in Figure 4. The initial HC values resemble those shown in Figure 2 for the calcium fly ash overlaying the clay liner. However, each freeze/thaw cycle substantially increases HC values for the system above the previous equilibration HC level. These results suggest that during the initial development and use of a disposal site, freezing conditions could result in the failure of the clay liner system.

Synthetic Liner Evaluations

The punch strength test data for the HDPE, VDPE and PVC materials are shown in Figure 5. This is the only property that permits direct comparison across the three materials tested, since the test was performed identically for each material type and at the same crosshead speed as required by the testing methods. The information demonstrates that the materials have much different capabilities to resist puncture. The heavy, thicker HDPE has the strongest punch strength as compared to the VDPE and the PVC materials. The PVC material, which is slightly thicker and stiffer, has more strength than the VDPE, which is a very low density polyethylene material. However, it is apparent that the influence of the various wastes on the integrity of the synthetic liner materials is not significant.

The influence of the various wastes on tear strength with grain and stress at 100% elongation with grain (Figures 6 and 7) was also found not to be significant. The HDPE had high tear strength as compared to the VDPE and the PVC, which have comparable tear strengths. However, the stress at 100% elongation with grain for the PVC material (untreated and treated) was the same as for the HDPE material, and both had higher stress strength than the VDPE material. This information provides an indication that the overall strength capabilities of the HDPE, VDPE and PVC materials after 120 days of treatment with the various wastes is similar to

those of the untreated liner materials. The HDPE material has higher strength as compared to the VDPE and PVC materials. However, the strength characteristics of the VDPE and PVC materials are not compromised by the waste materials and could be used in waste landfill applications where they are suited. More detailed results for the tests associated with each liner material is presented in the following discussion.

High Density Polyethylene

Elongation at yield data for both with-grain and cross-grain testing is shown in Figures 8 and 9, respectively. The baseline sludge material seemed to increase the elongation slightly with time, but the other injection materials did not seem to have any significant, lasting effect on elongation.

Test results for elongation at break testing were characterized with a large scatter of the data, therefore meaningful trends could not be identified (Appendix A).

The yield strength tested with grain is shown in Figure 10. The data indicate that the yield strength was not influenced by the baseline fly ash materials, by the Na_2CO_3 or by the Ca injection materials. However, the Na_2CO_3 -urea injection materials caused an initial drop in yield strength that disappeared by the end of the 120-day testing period. The cross-grain yield strength data shown in Figure 11 indicated identical results.

Breaking strength tested with grain and cross grain are presented in Figures 12 and 13, respectively. Here again, the baseline, Na_2CO_3 and Ca-injection materials had no affect over time on the breaking strength in either orientation. But the Na_2CO_3 -urea injection material appeared to initially depress the breaking strength. This effect disappeared during the 120-day test for both orientations. The %CV values were low for the with-grain results and were significantly higher for the cross-grain tests (Appendix A).

Tensile stress tests at 100% and 200% elongation for the with-grain and cross-grain testing are shown in Figures 14-17. The tensile stress at 100% and 200% elongation tested in both orientations were unaffected by the condition sludges. The only exception was with the specimens conditioned with Na_2CO_3 -urea injection materials. These specimens displayed an initial drop in tensile stress that appeared to be a transient effect, since the decreased strength was no longer evident at 120 days.

Elastic modulus results for both orientations are presented in Figures 18 and 19. The data for the with-grain tests show that the conditioning materials had a transient effect on the elastic response of the tested materials over time. For the cross-grain tests there appeared to be a transient effect caused by the baseline, Na_2CO_3 , and Ca-injection materials that lowered the elastic modulus. However, after 120 days of conditioning, the reduction of the elastic modulus values was no longer apparent.

The tear strength tests with grain and cross grain are shown in Figures 20 and 21, respectively. The orientation of the test specimen did not affect the tear strength. However, a transient decrease in tear strength was observed for the sample conditioned in the Na_2CO_3 injection material.

Very Low Density Polyethylene (VDPE)

Elongation at yield results for specimens tested in the with-grain and cross-grain orientations are presented in Figures 22 and 23, respectively. In general, the baseline and injection materials had no lasting influence on elongation at yield. However, the 90-day Na_2CO_3 injection material caused elongation at yield for both orientations to be inexplicably high. This was noted at the time of testing, and the test method was reviewed prior to continuing with the tests. It should be pointed out that the technique used to measure elongation was not as predicted at the low-yield elongations, as it was at the higher elongations. Therefore, these data are only considered to be a qualitative check on the behavior of the material.

Elongation and strength at break data are not presented since in all but a few cases the maximum displacement of the test frame was reached without specimen failure.

Yield strength data for both orientations are presented in Figures 24 and 25. The data indicate that the conditioning regime had no effect on this property. However, a temporary exception occurred at 60 days with the Na_2CO_3 -urea treated specimens, which exhibited a significant drop in yield strength.

Stress at 100% and 200% elongation values tested in both orientations are presented in Figures 26 through 29. The results indicate that conditioning of the material had no permanent effect on stress at elongation properties. Much like the yield strength results discussed previously, there appeared to be a temporary drop in stress at 60 days of conditioning for the Na_2CO_3 -urea treated specimens.

Elastic modulus results for with-grain and cross-grain VDPE material are presented in Figures 30 and 31. The testing did not show any clear trends for the treated VDPE material, except that initially all the conditioned materials but the Na_2CO_3 -urea exposed specimens were stiffer. This condition usually is caused by the loss of plasticizer. However, this condition was found to be transient.

Tear strength results when tested with-grain and cross-grain, are presented in Figures 32 and 33. The tear strength remained almost constant through 120 days of conditioning. However, a slight dip in strength was observed with the 60-day Na_2CO_3 -urea tests.

Polyvinyl Chloride (PVC)

Results for the elongation at break testing with-grain and cross-grain for the PVC materials are presented in Figures 34 and 35. The tabulated averages and %CV values are presented in Appendix A. No significant trend was observed for the with-grain testing. The outlier data collected from the 90 day testing must be discounted due to the high %CV associated with the data. For the cross-grain test results, the only consistent effect created by the conditioning was a small reduction in elongation with time for the Na_2CO_3 injected material conditioned specimens.

Breaking strengths for the with-grain and cross-grain specimens are shown in Figures 36 and 37. For both orientations, the conditioning had transient effects on this property. The 90-day results for all conditioning solutions except Na_2CO_3 -urea were greatly depressed. This was not a permanent effect, since the 120-day results were back to the untreated levels. The data were thoroughly checked. There was no indication of a testing error, and the HDPE material tested at the same time came out as expected. The 60-day Na_2CO_3 -urea conditioned specimens also showed a temporary drop in strength.

Results of the stress at 100% and 200% elongation testing for both orientations are shown in Figures 38 through 41. The same trend that appeared in the above breaking strength data occurred in the stress at 100% and 200% elongation data. These properties appeared to be unaffected by the conditioning except at 90 days, when the stress values dropped significantly, only to raise again at 120 days. Also, the specimens treated with Na_2CO_3 materials had an increased stress at 100% and 200% elongation at 120 days. As with the previous tests, the 60-day Na_2CO_3 -urea conditioned samples displayed a temporary drop in strength.

Tear strength results for the with-grain and cross-grain tests are reported in Figures 42 and 43. The same pattern exists for the tear strength results as was seen with the tensile results. The tear strength after 120 days showed no ill effects from the conditioning regime. All apparent decreases in strength occurred for the 60- and 90-day samples.

Volatiles Content Tests

An increase in volatile losses is an indication of water absorption into the liner materials. The percentage volatiles present in the liner samples before and after exposure to the sludge materials are presented in Table 2. The volatile losses associated with the PVC material are similar after a 120-day period of conditioning in the baseline, Na_2CO_3 , and the Na_2CO_3 -urea sludge materials. The volatile losses associated with the Ca injection waste treatment appear to be higher. However, volatile losses for all the treated materials were rather small, with the largest loss found to be about 0.25%.

Table 2. Weight Losses Due to Volatiles and Extractables

<u>Membrane/Treatment</u>	<u>Volatiles, % Weight Loss</u>	<u>Extractables, % Weight Loss</u>
PVC-Baseline	0.19	30.76
PVC-Na ₂ CO ₃ Injection	0.20	30.19
PVC-Na ₂ CO ₃ Injection	0.20	30.33
PVC -Na ₂ CO ₃ Urea Injection	0.20	30.21
PVC-Ca Injection	0.26	30.36
HDPE-Baseline	0.14	0.34
HDPE -Na ₂ CO ₃ Injection	0.08	0.53
HDPE -Na ₂ CO ₃ Injection	0.10	0.61
HDPE -Na ₂ CO ₃ Urea Injection	0.08	0.53
HDPE -Ca Injection	-0.01	0.60
VDPE-Baseline	0.07	1.31
VDPE -Na ₂ CO ₃ Injection	0.07	1.23
VDPE -Na ₂ CO ₃ Injection	0.16	1.12
VDPE -Na ₂ CO ₃ Urea Injection	0.13	1.06
VDPE -Ca Injection	0.05	1.38

For the HDPE liner materials, the influence of the sludge generated under baseline conditions had a weight loss of 0.14% which was higher than that of the CCT sludge treatments. The treatments using Na₂CO₃ and Na₂CO₃-urea sludges resulted in volatile losses of about 0.1% and 0.08%, respectively, and the Ca injection material gained 0.01% weight after 120 days of treatment. These data demonstrate that the water absorption into the HDPE liner materials is very limited.

The VDPE liner material also tended not to absorb much water. The liner treated with Ca injection, Na₂CO₃, and baseline materials lost about equal amounts of weight at about 0.06%. The liner treated with Na₂CO₃ had a volatile loss of about 0.16%, which is significantly higher than the losses resulting from treatment with the other wastes used.

Extractables Content Tests

Weight loss from the liner materials due to extractables is an indication that liner components are leached from the liner as a result of exposure to a waste. The weight loss associated with liner materials is presented in Table 2. The PVC liner material reacted similarly

for all treatments, with about a 30% weight loss due to extractables. The HDPE and VDPE liner materials reacted much differently. The extractable losses for the HDPE were about 0.5% for each treatment, and the losses for the VDPE materials varied from about 1.06% for the Na₂CO₃-urea material to about 1.38% for the Ca injection waste. The extractables associated with the untreated liner specimens are currently being tested and will be included in the final report.

CONCLUSIONS

The impact of CCT materials on the characteristics of the clay liner materials studied in this project was minimal. The HC measurements of the waste/clay liner systems were similar to those of the water/clay liner systems. Although some swelling was evident in the sodium materials, the sludge materials did not have a negative impact on the integrity of the liners over 120-day tests. Wet/dry cycles tended to result in lower HC, while freeze/thaw cycles substantially increased HC for the liners tested.

Sustained incremental changes in the measured physical properties of the synthetic liner materials over time were not observed. Some abrupt changes in strength were found several times during the testing period. However, these aberrations seemed more indicative of isolated changes in the conditioning methods or test procedures and could be related to flaws or changes in the materials related to manufacturing conditions. After 120 days of conditioning, none of the measured physical properties varied significantly from those for the untreated liner materials. This was true for all samples regardless of the conditioning solution used. It is apparent from the results of this study that the HDPE liner material would be expected to perform better than the VDPE and PVC liner materials due to its higher strength characteristics.

The volatiles and extractables tests for the HDPE and VDPE materials indicated that the waste materials had little influence on their overall structure. However, the extractables data suggest that PVC liner material might decompose in the waste environments evaluated. The PVC liner material reacted similarly for all treatments, with about a 30% weight loss.

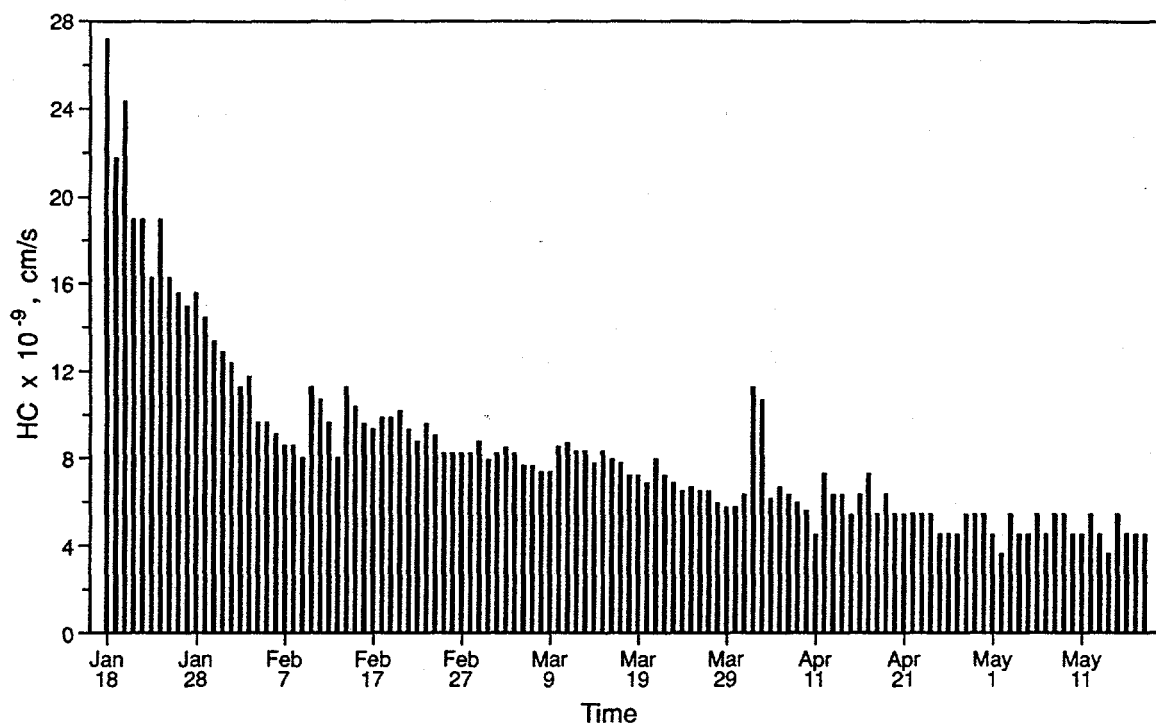


Figure 1. Long-Term Hydraulic Conductivity Values for a Clay Liner Impacted by Sodium Injection Fly Ash Leachate

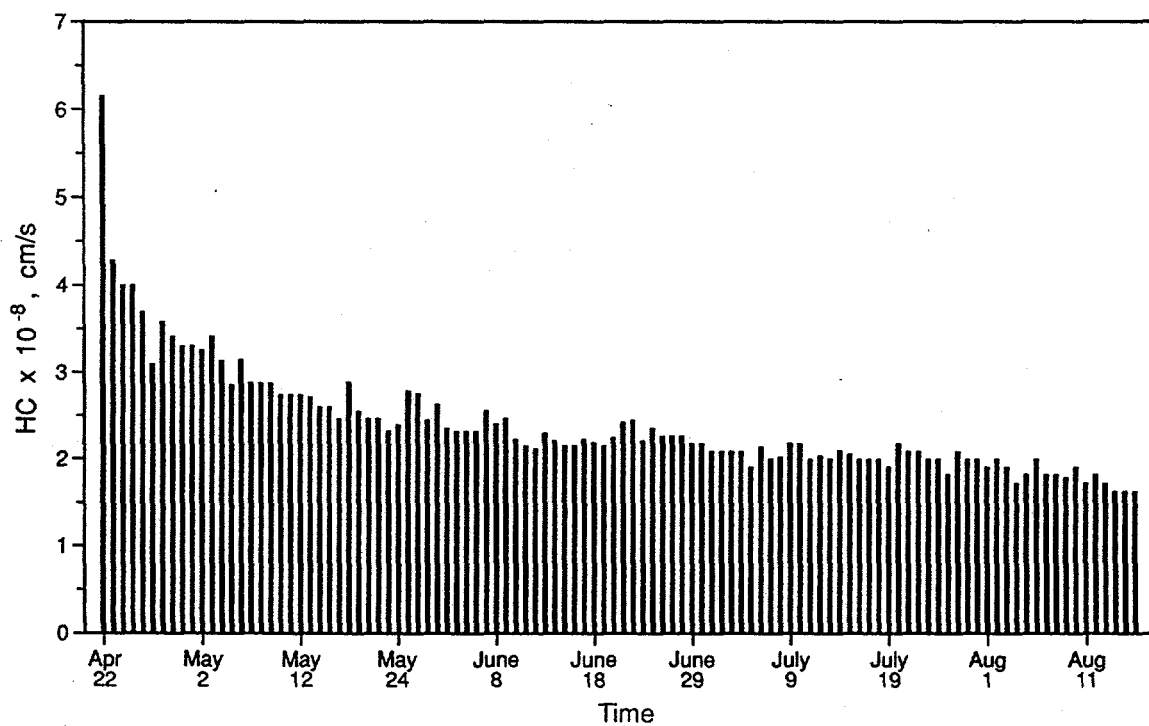


Figure 2. Long-Term Hydraulic Conductivity Values for a Clay Liner Material Overlain by Calcium Injection Fly Ash

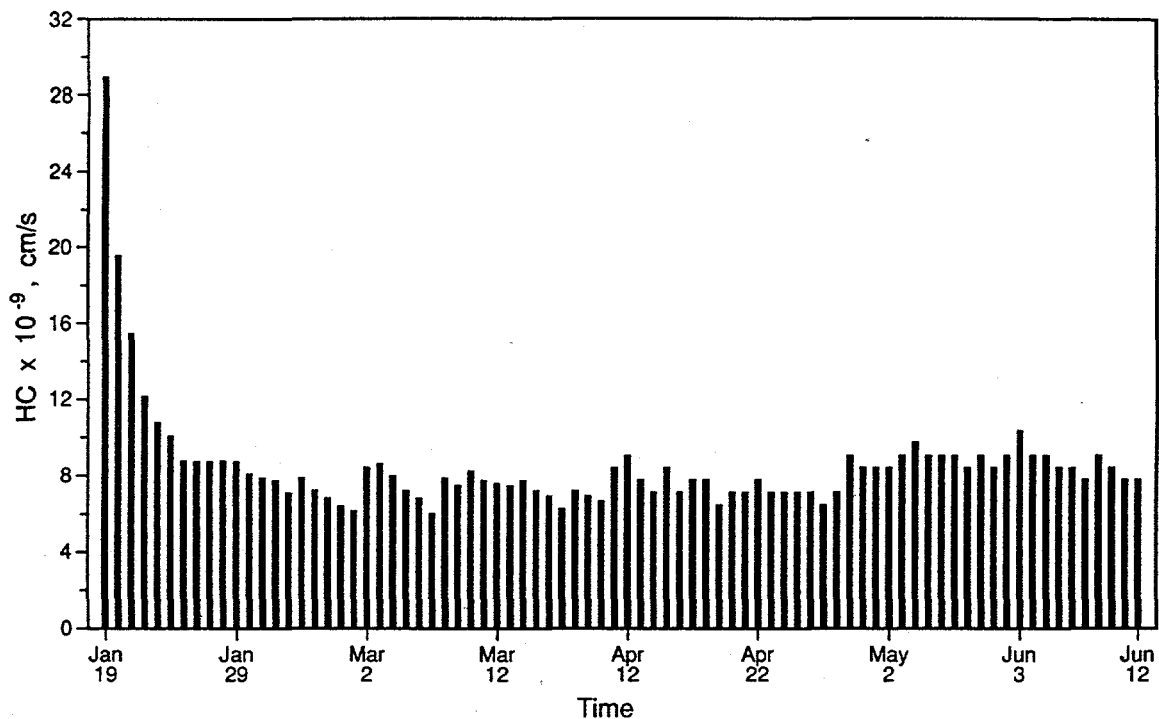


Figure 3. Hydraulic Conductivity Values for a Clay Liner Material Impacted by Leachate from Sodium Injection Fly Ash Undergoing Wet/Dry Cycles

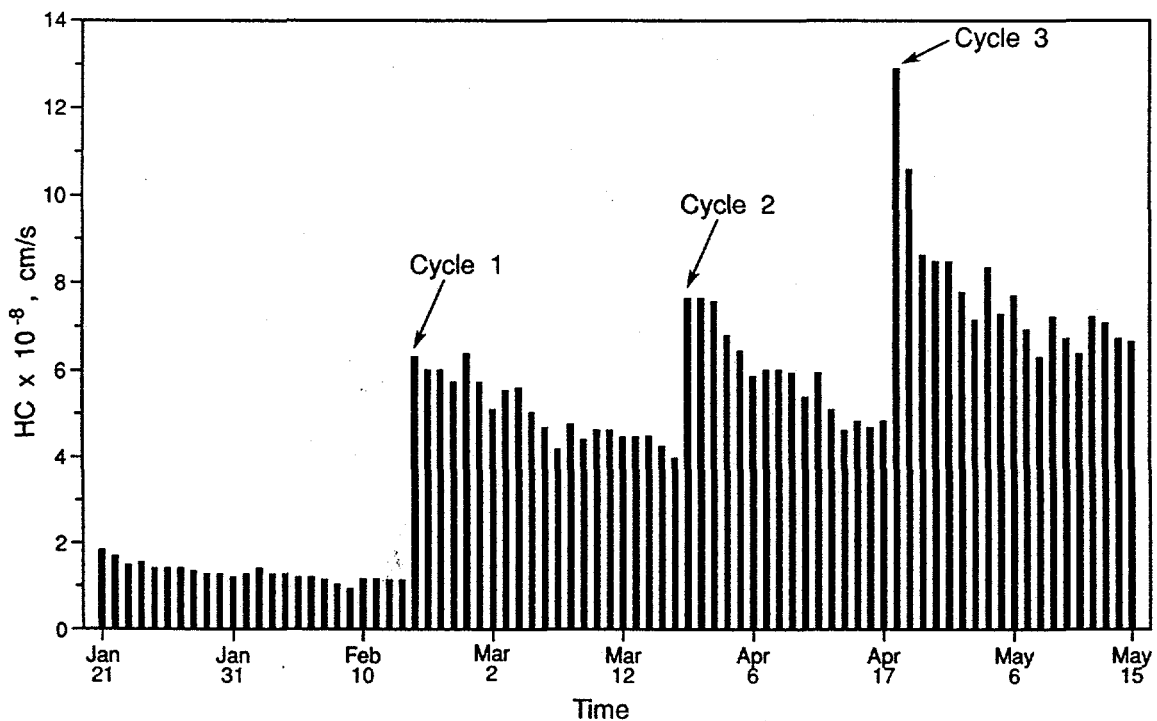


Figure 4. The Influence of Freeze/Thaw Cycles on the Hydraulic Conductivity of Clay Liner Material Impacted by Solution Extracted From Calcium Injection Fly Ash

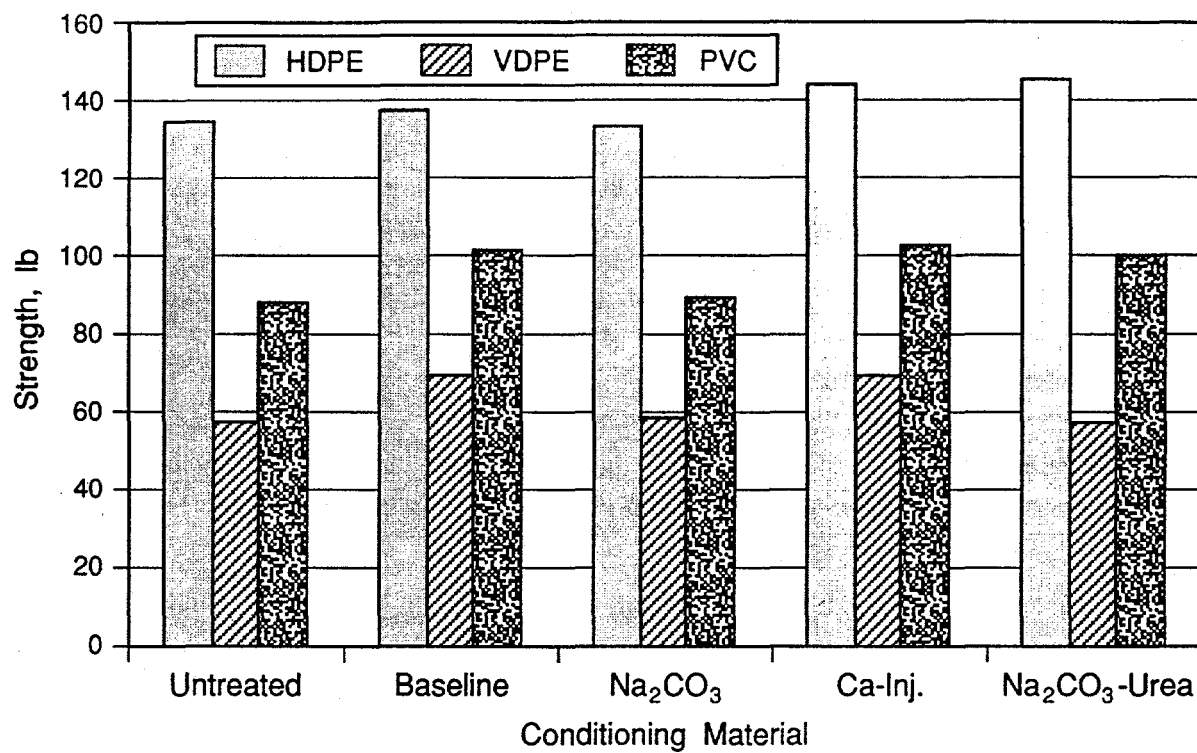


Figure 5. Punch Strength - 120 Days

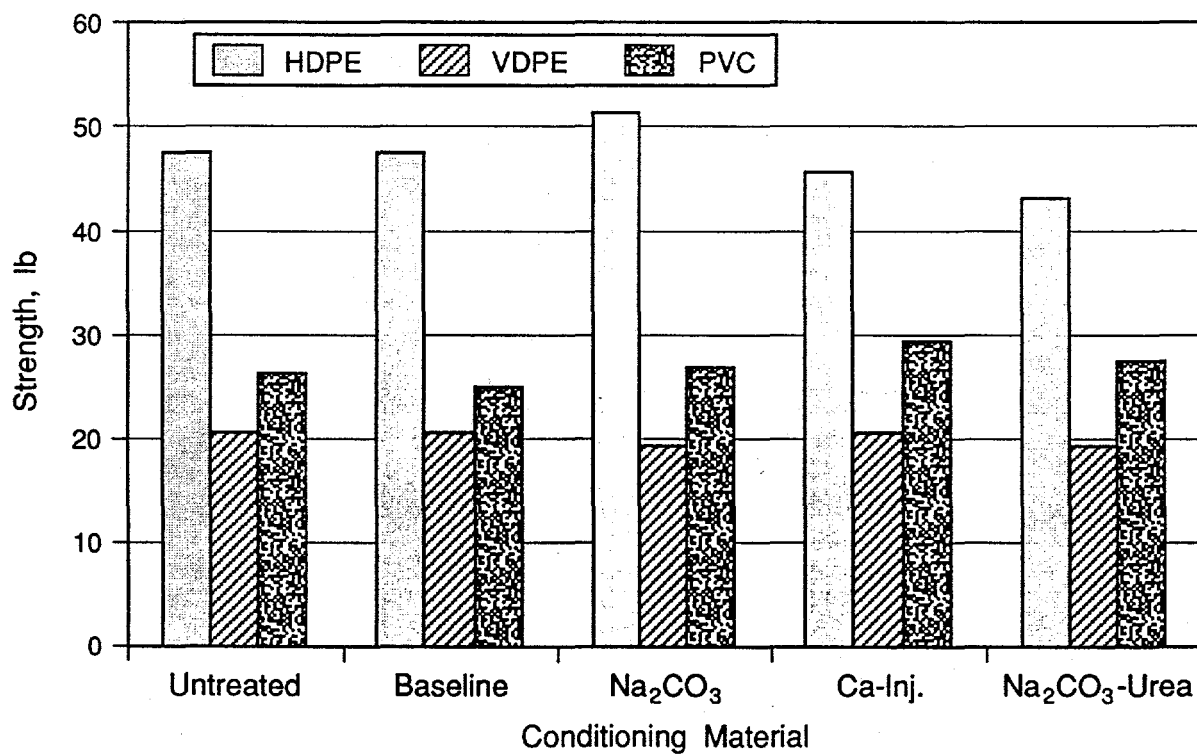


Figure 6. Tear Strength With-Grain - 120 Days

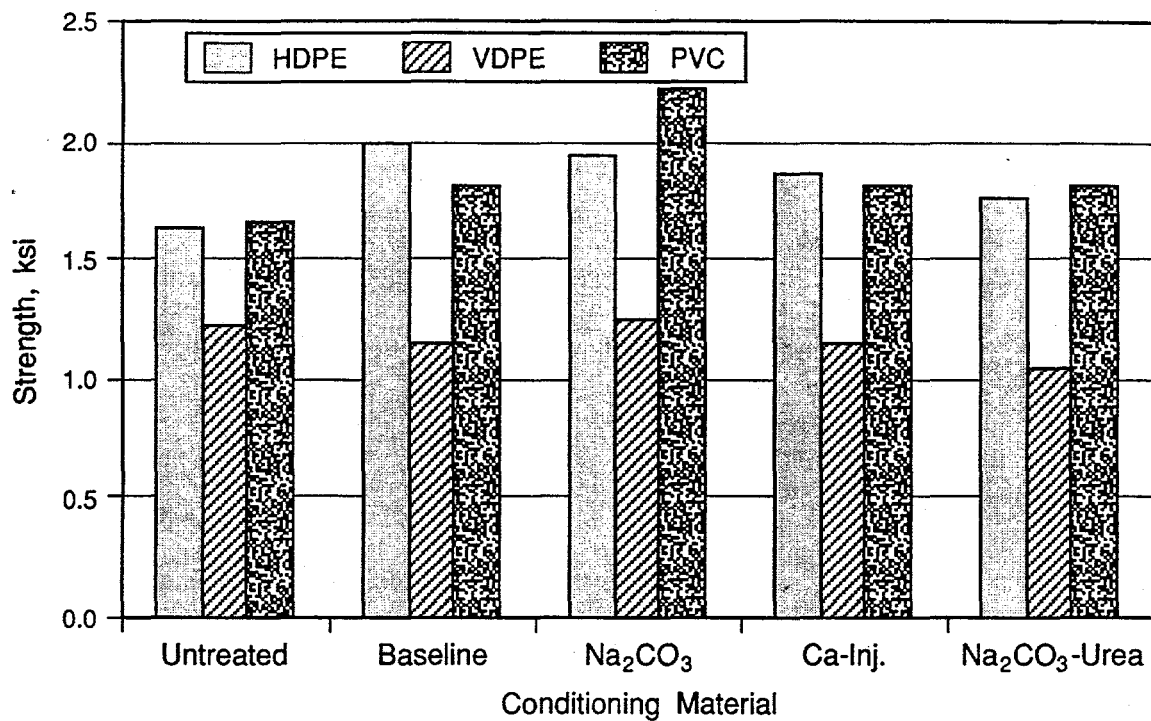


Figure 7. Stress at 100% Elongation With-Grain – 120 Days

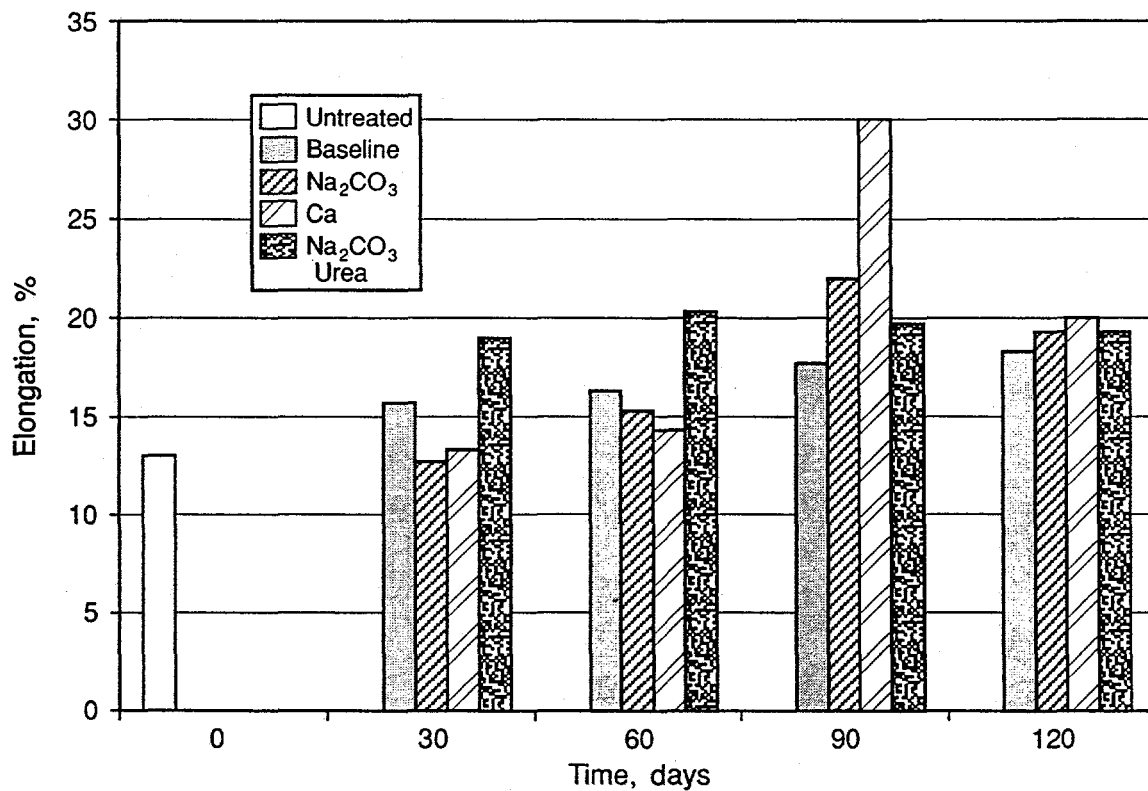


Figure 8. Elongation at Yield With-Grain for HDPE

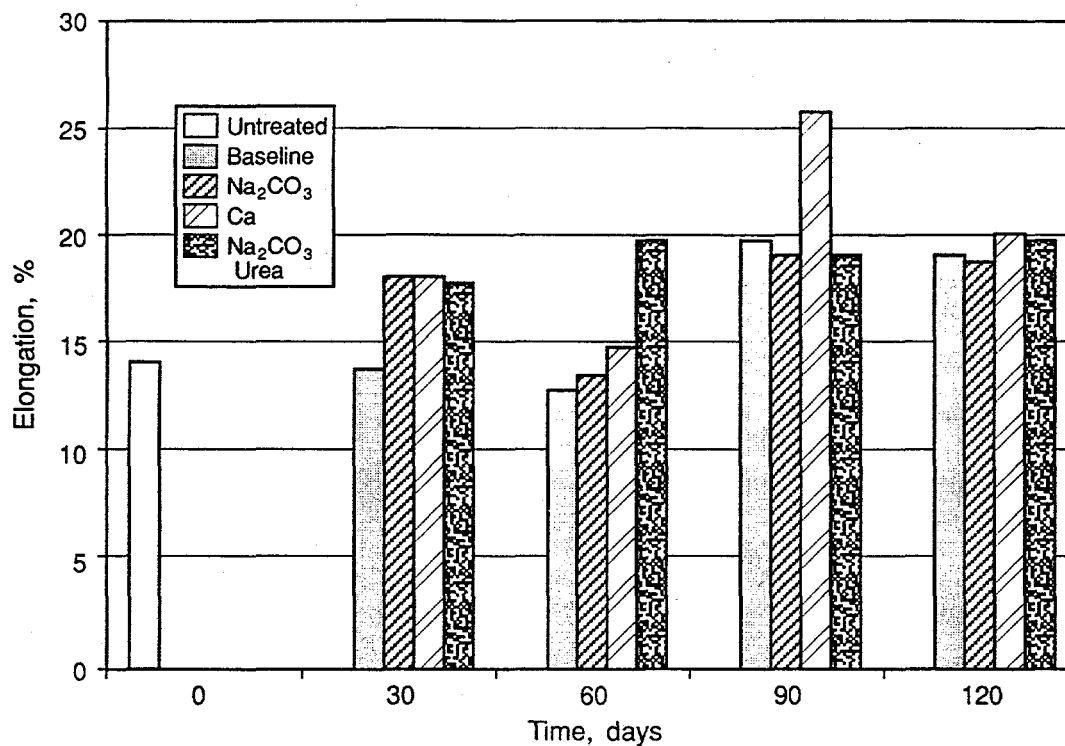


Figure 9. Elongation at Yield Cross-Grain for HDPE

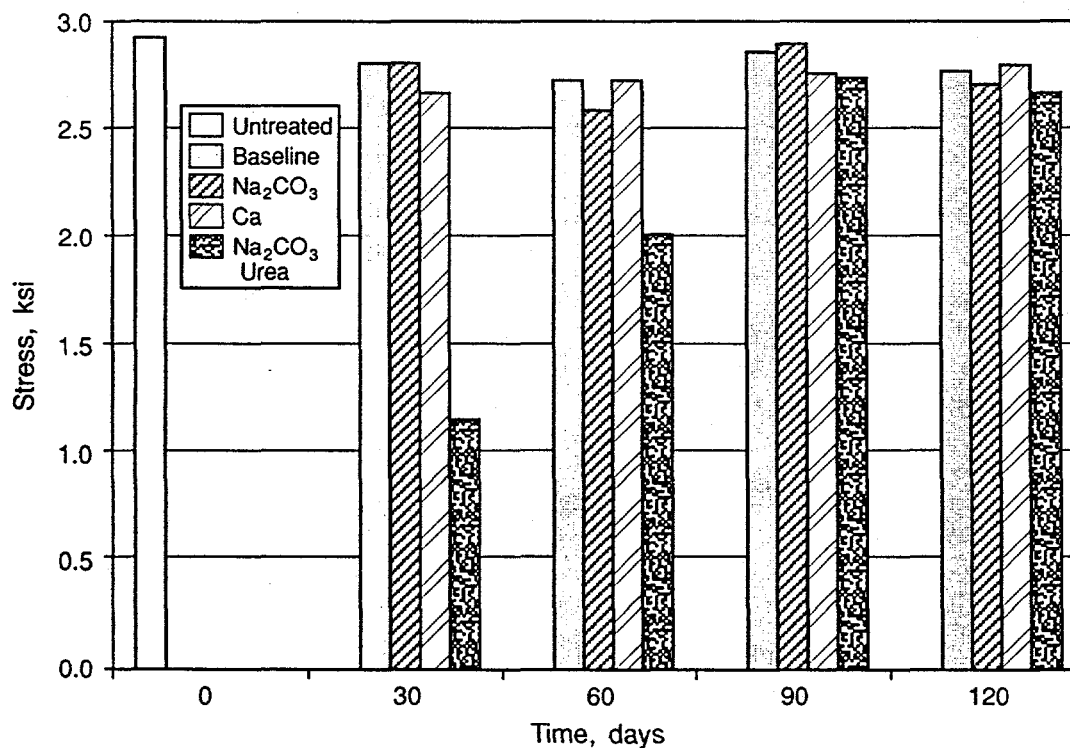


Figure 10. Yield Strength With-Grain for HDPE

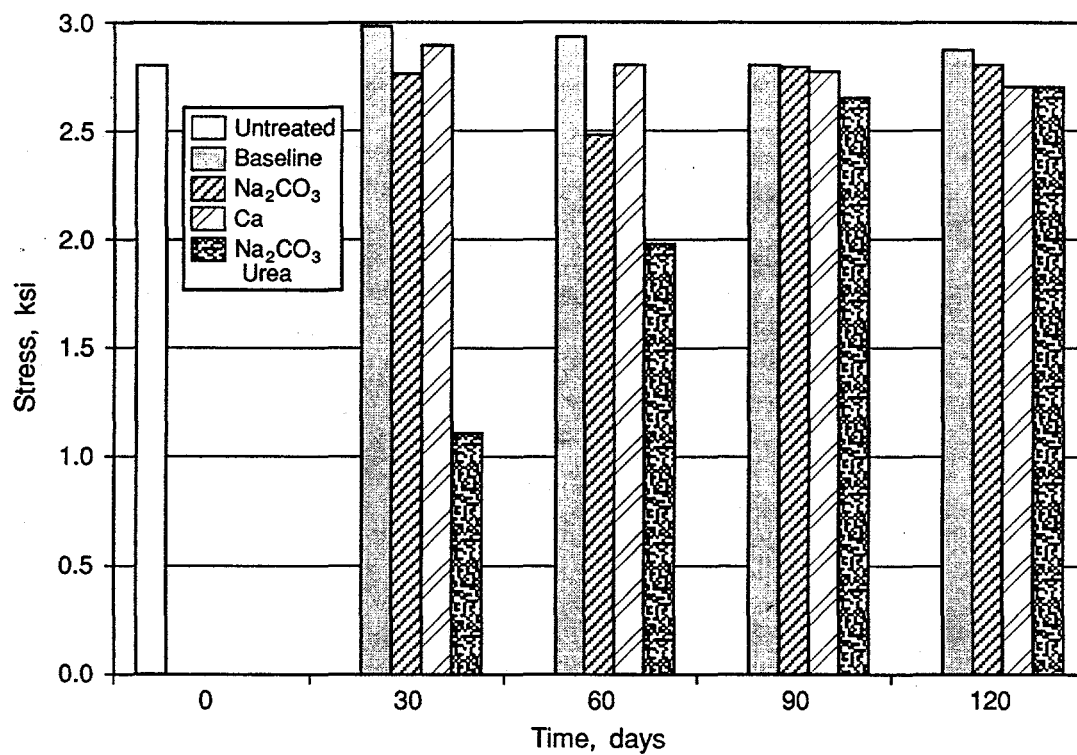


Figure 11. Yield Strength Cross-Grain for HDPE

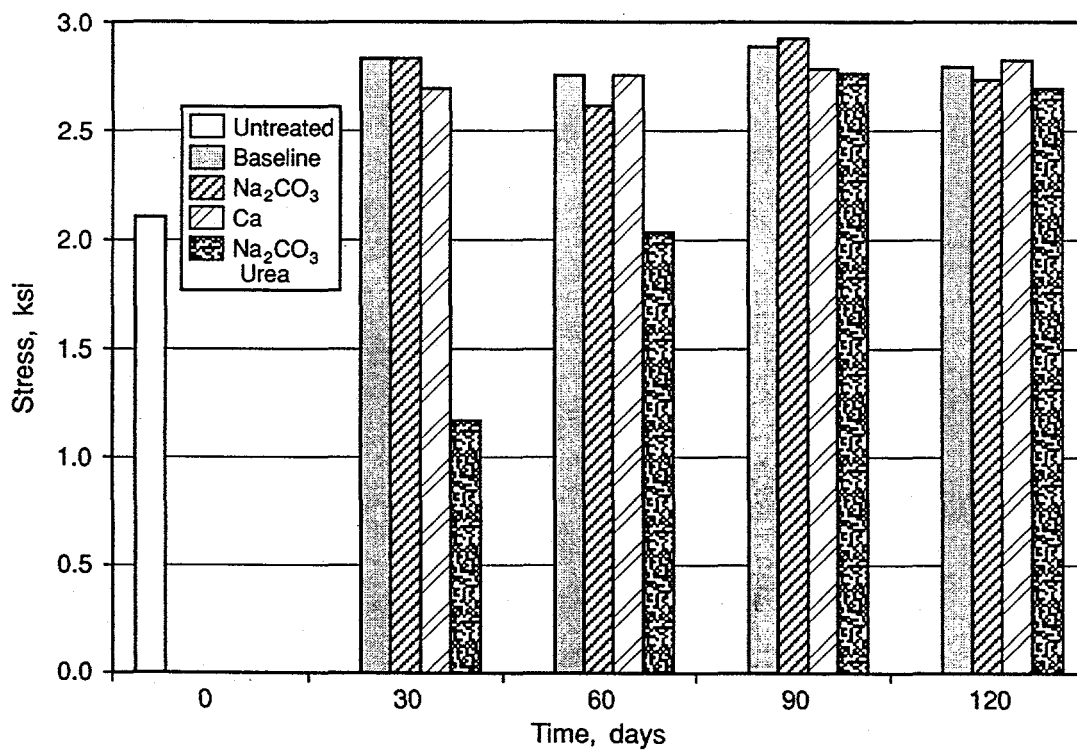


Figure 12. Breaking Strength With-Grain for HDPE

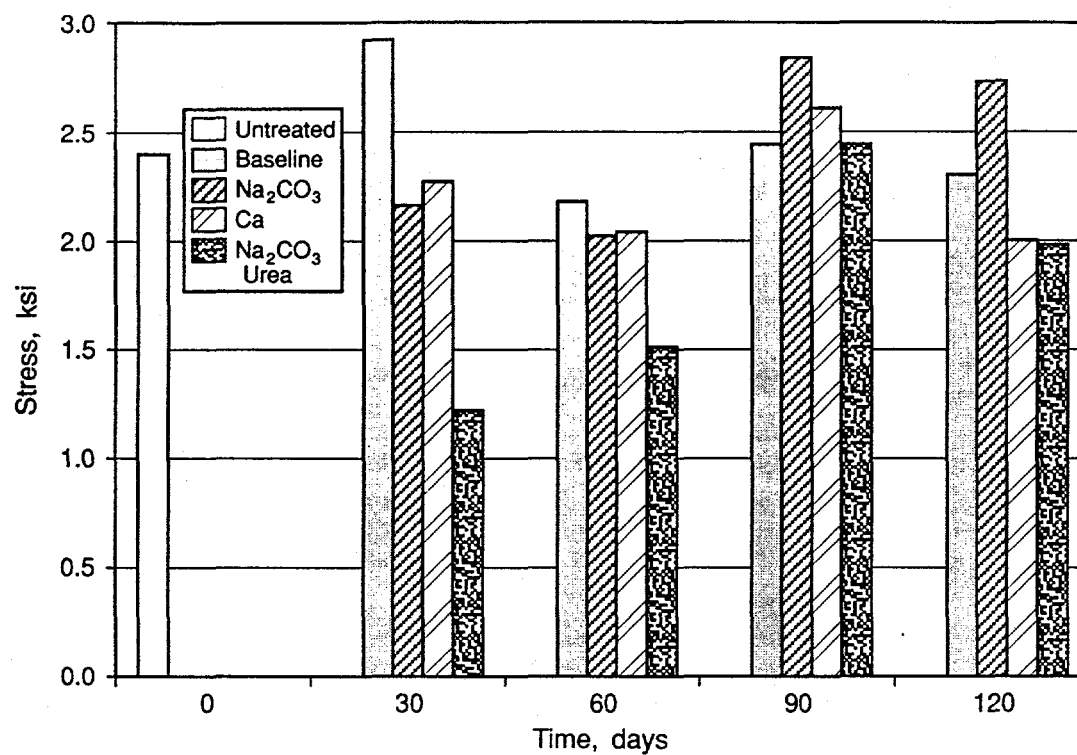


Figure 13. Breaking Strength Cross-Grain for HDPE

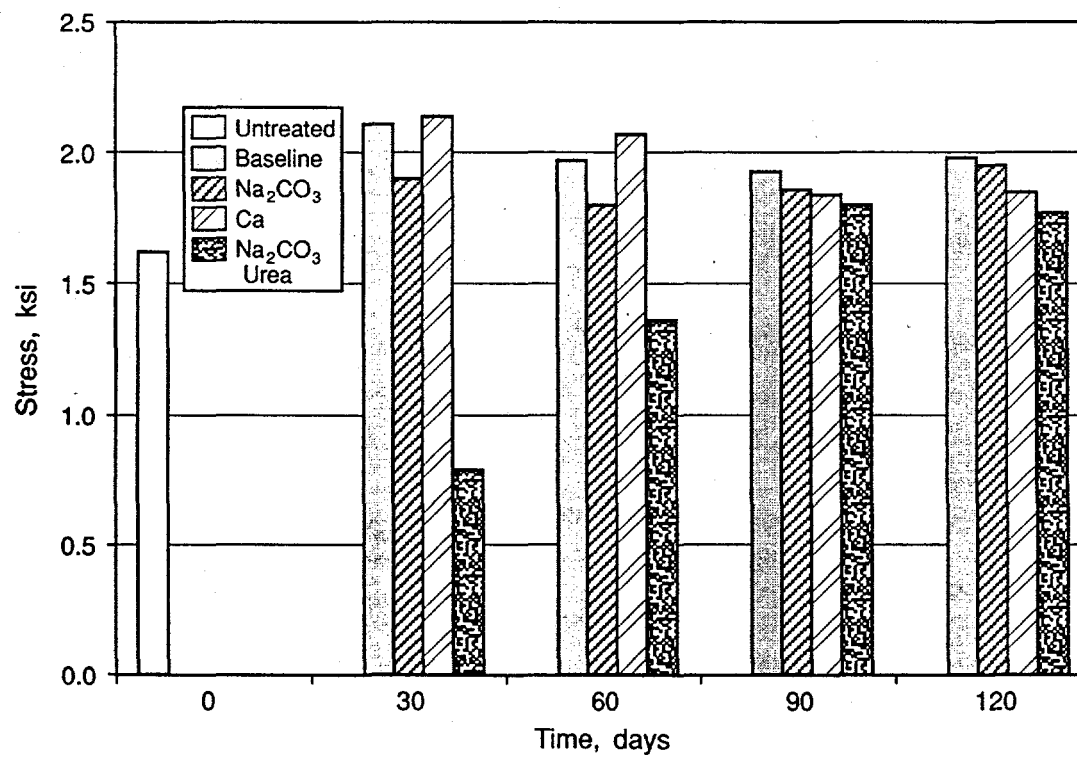


Figure 14. Stress at 100% Elongation With-Grain for HDPE

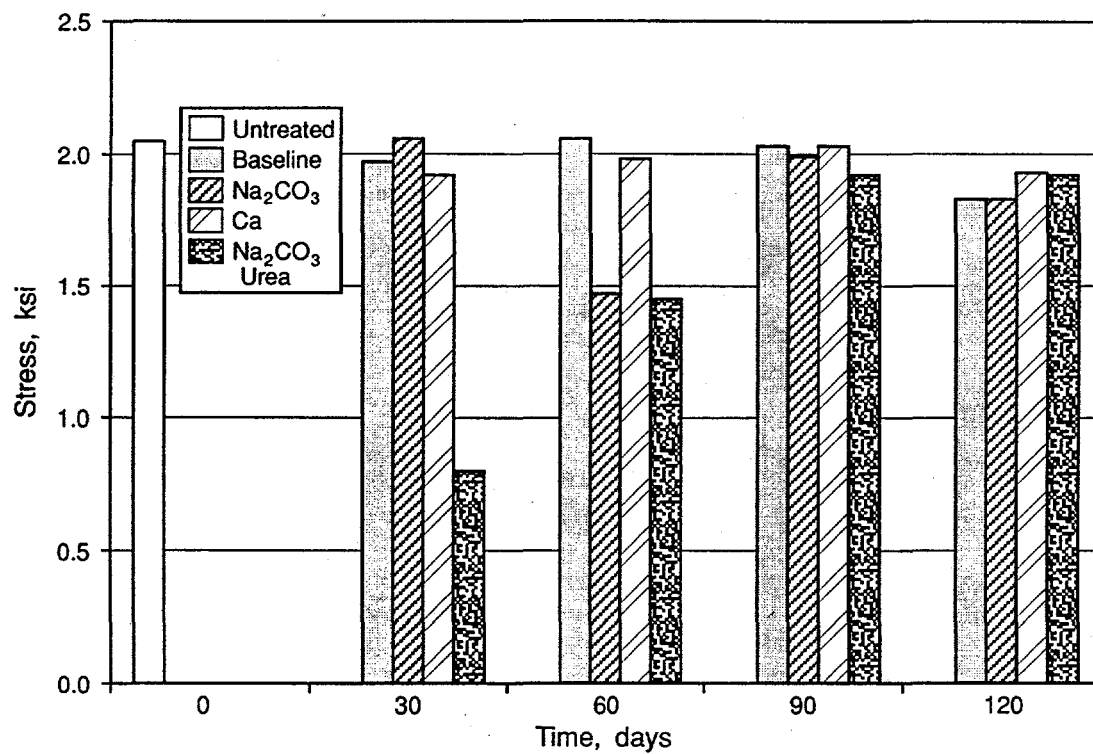


Figure 15. Stress at 100% Elongation Cross-Grain for HDPE

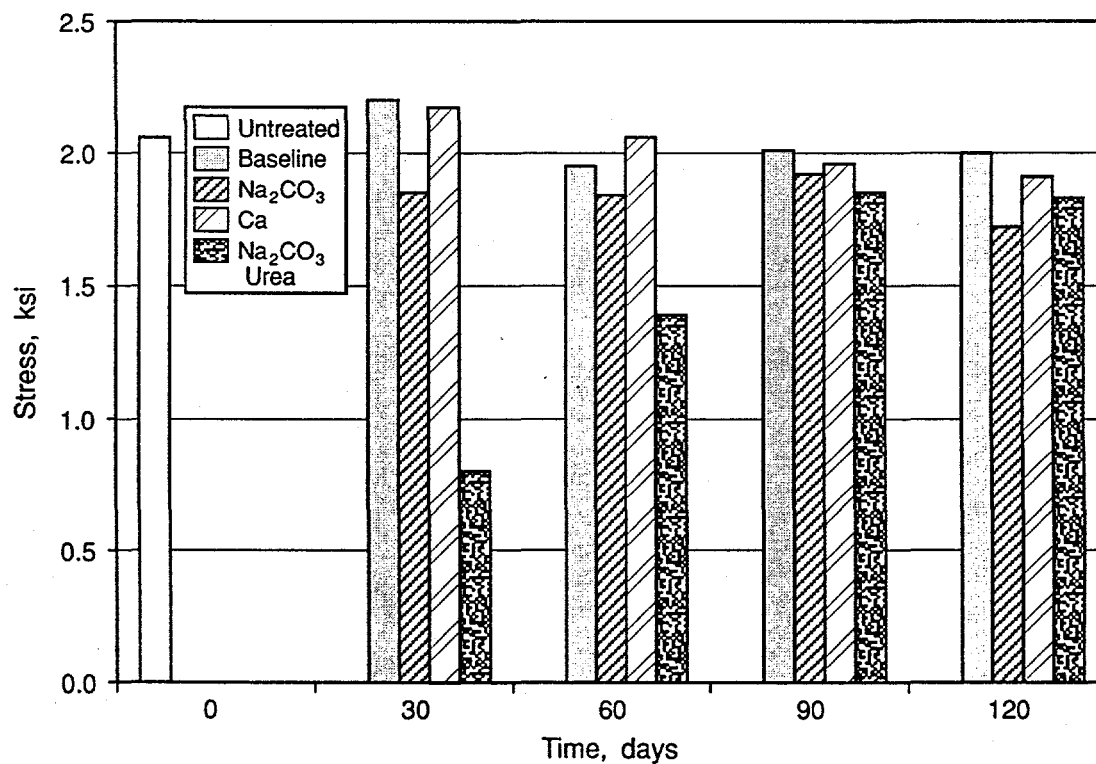


Figure 16. Stress at 200% Elongation With-Grain for HDPE

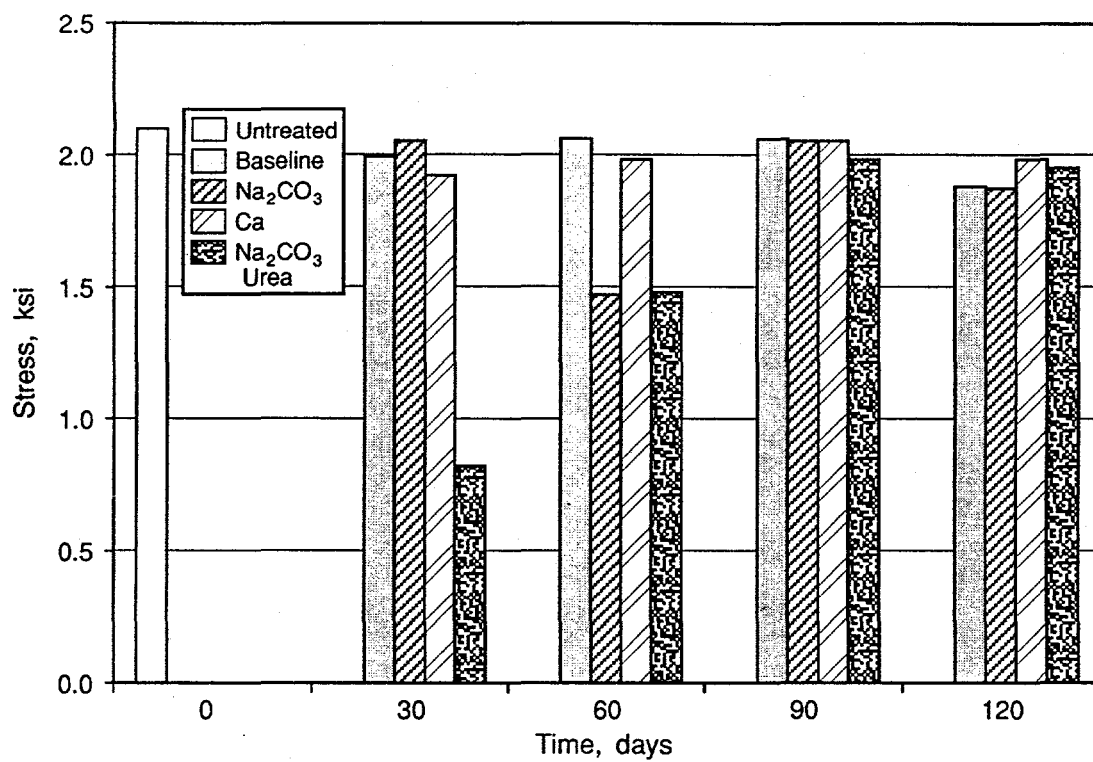


Figure 17. Stress at 200% Elongation Cross Grain for HDPE

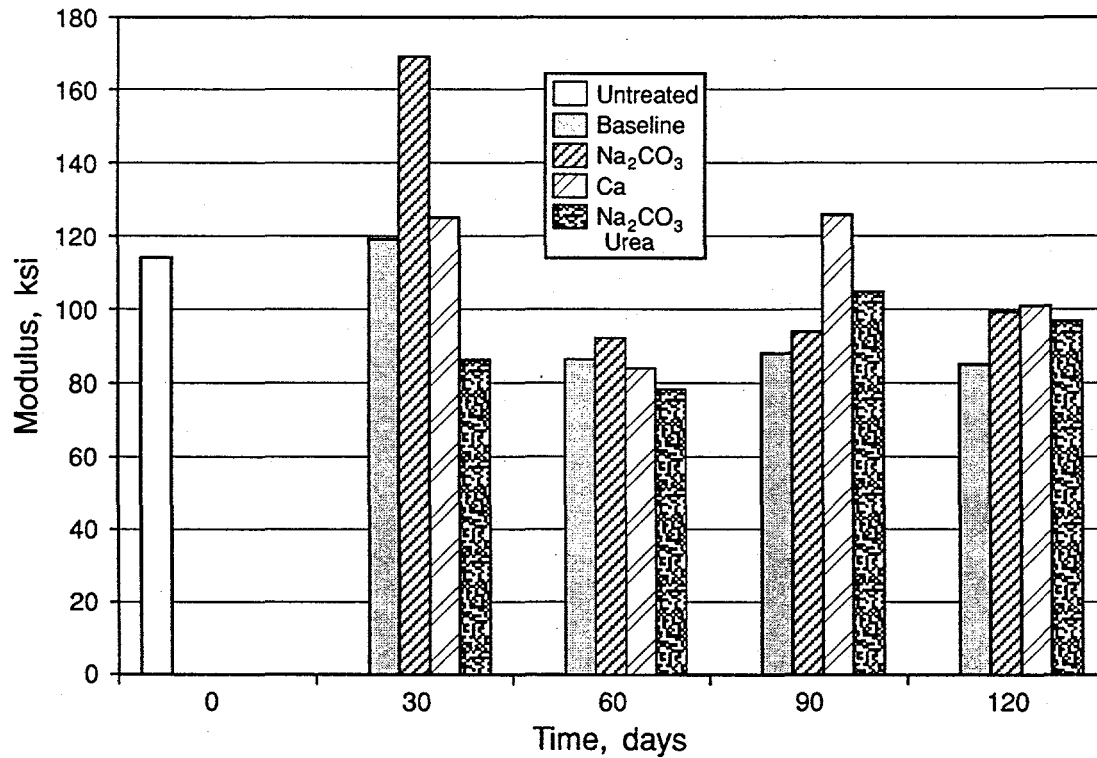


Figure 18. Elastic Modulus With-Grain for HDPE

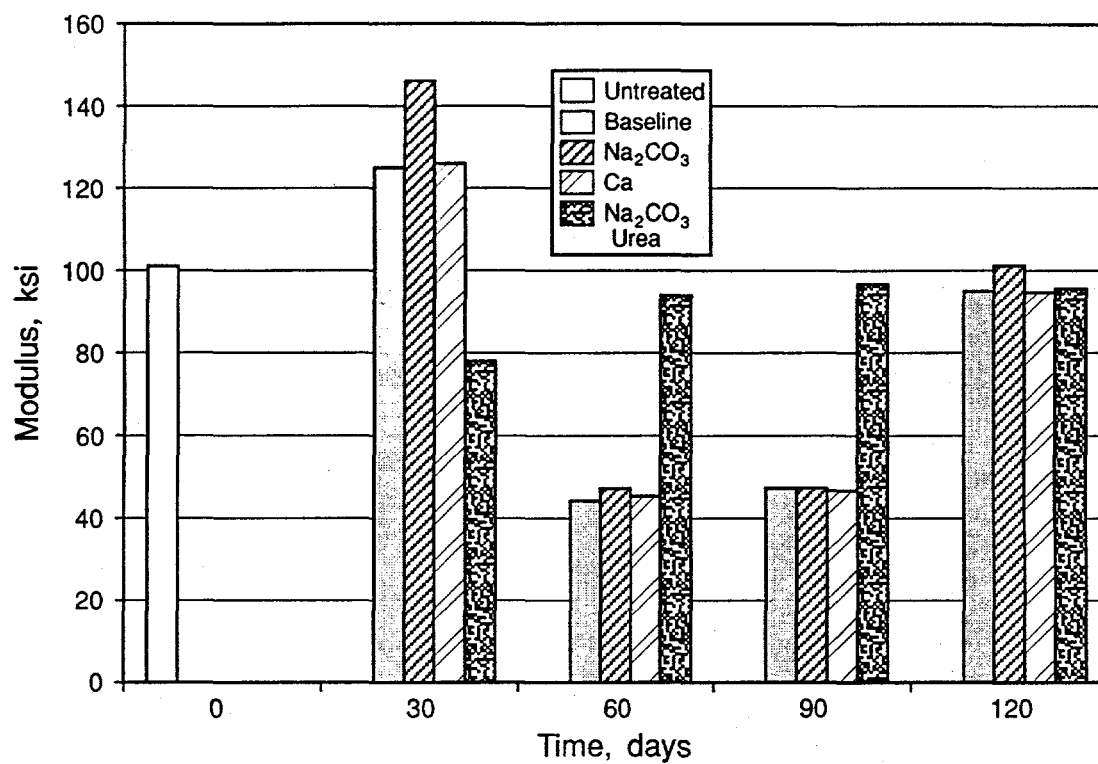


Figure 19. Elastic Modulus Cross-Grain for HDPE

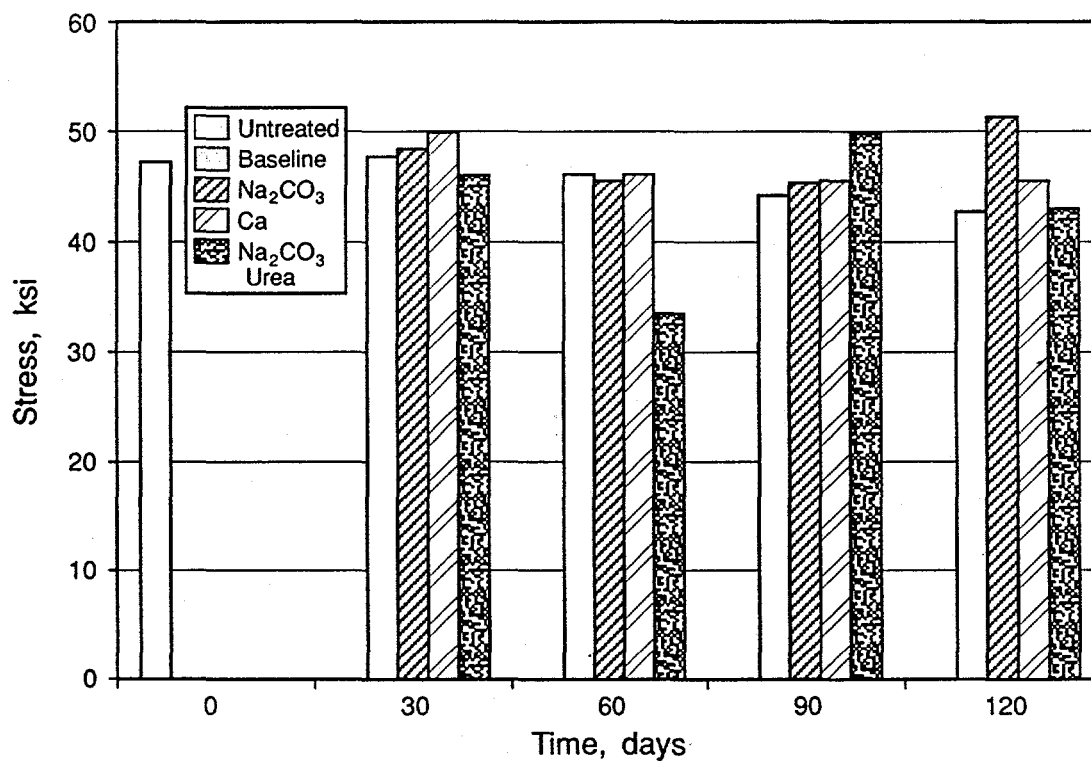


Figure 20. Tear Strength With-Grain for HDPE

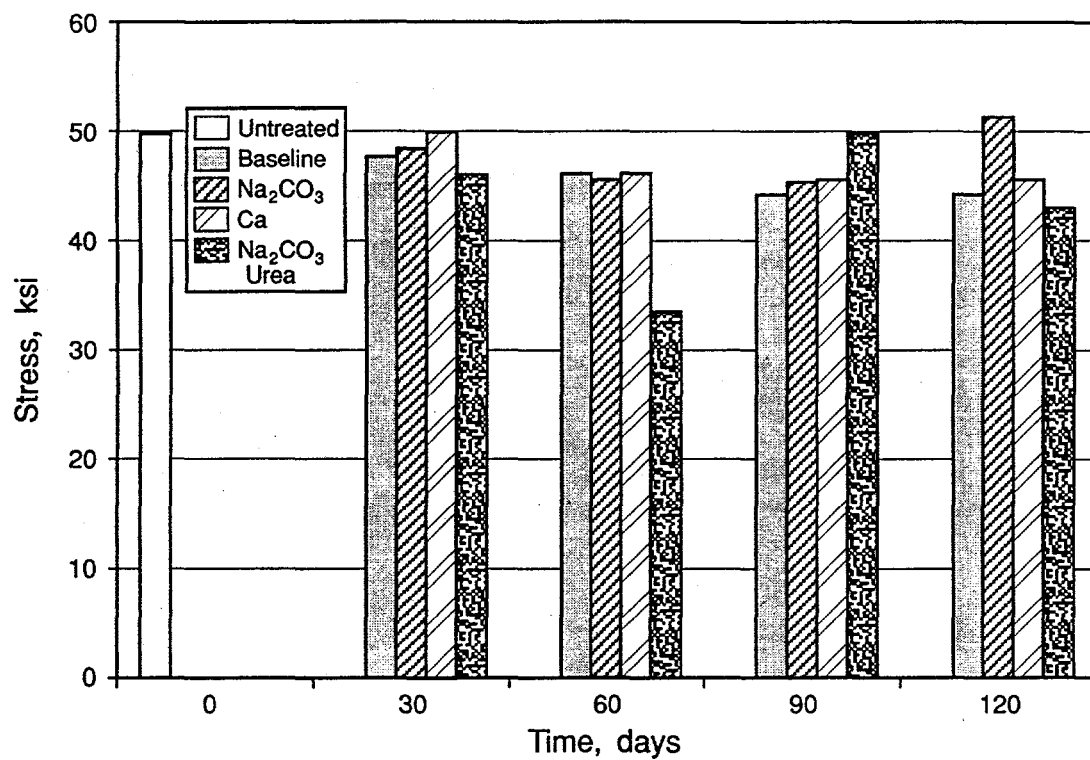


Figure 21. Tear Strength Cross Grain for HDPE

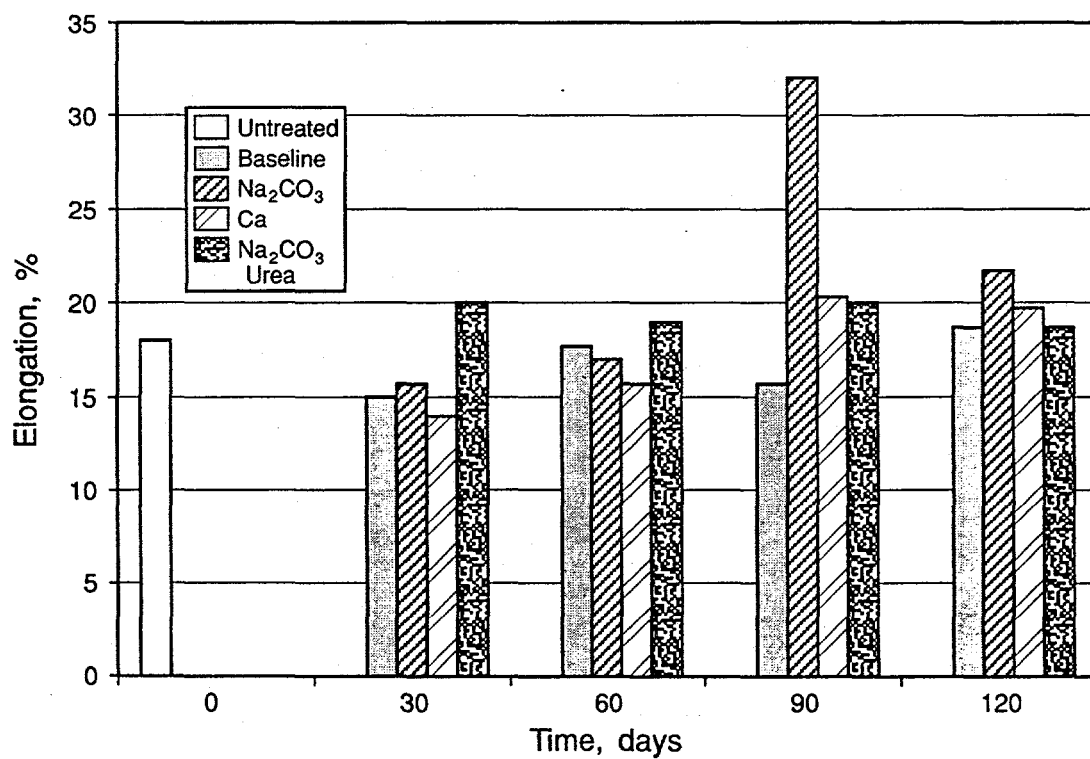


Figure 22. Percent Elongation at Yield With Grain for VDPE

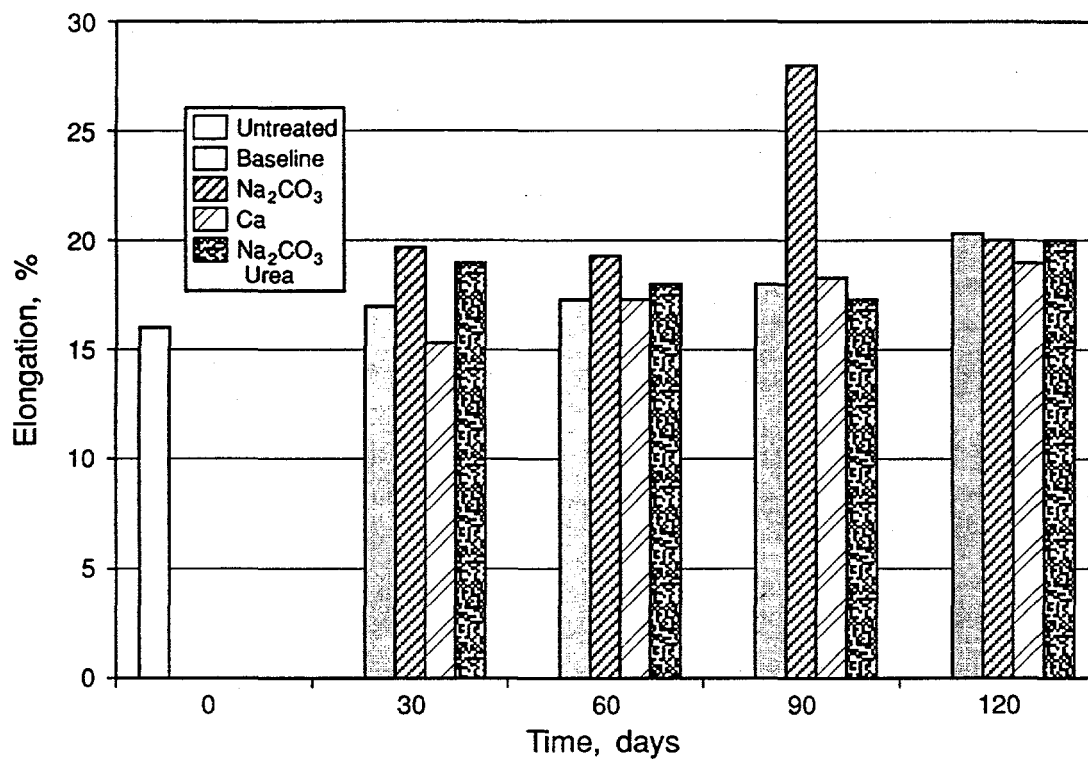


Figure 23. Percent Elongation at Yield Cross-Grain for VDPE

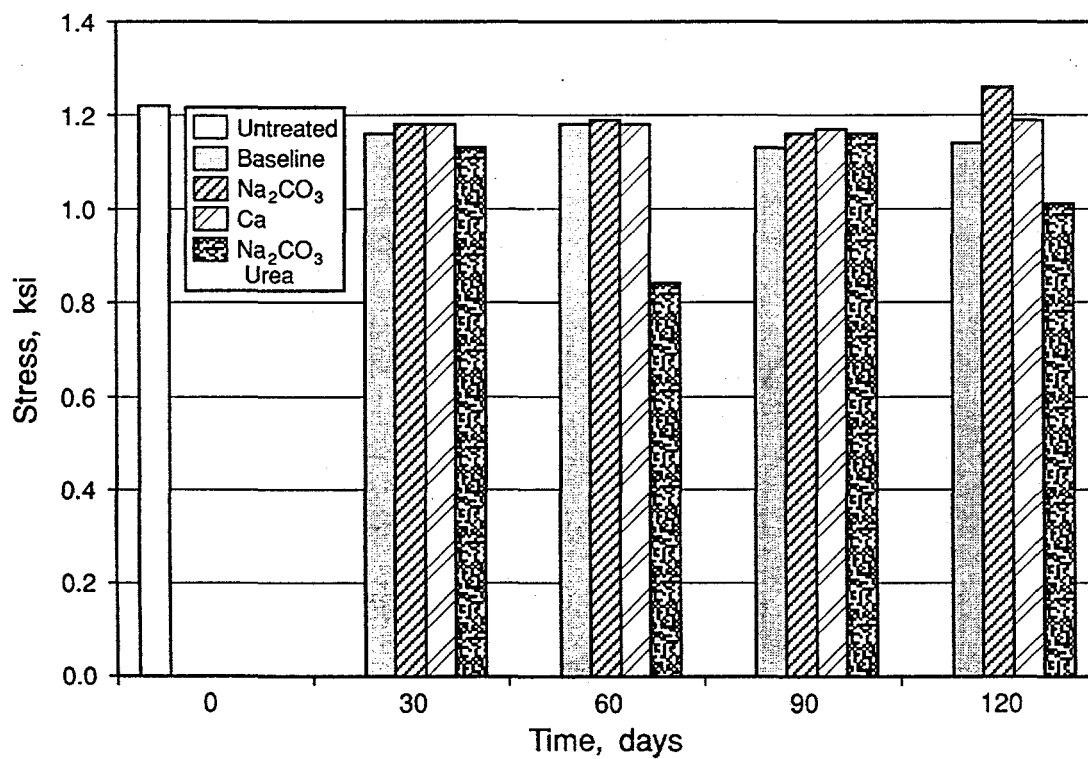


Figure 24. Yield Strength With-Grain for VDPE

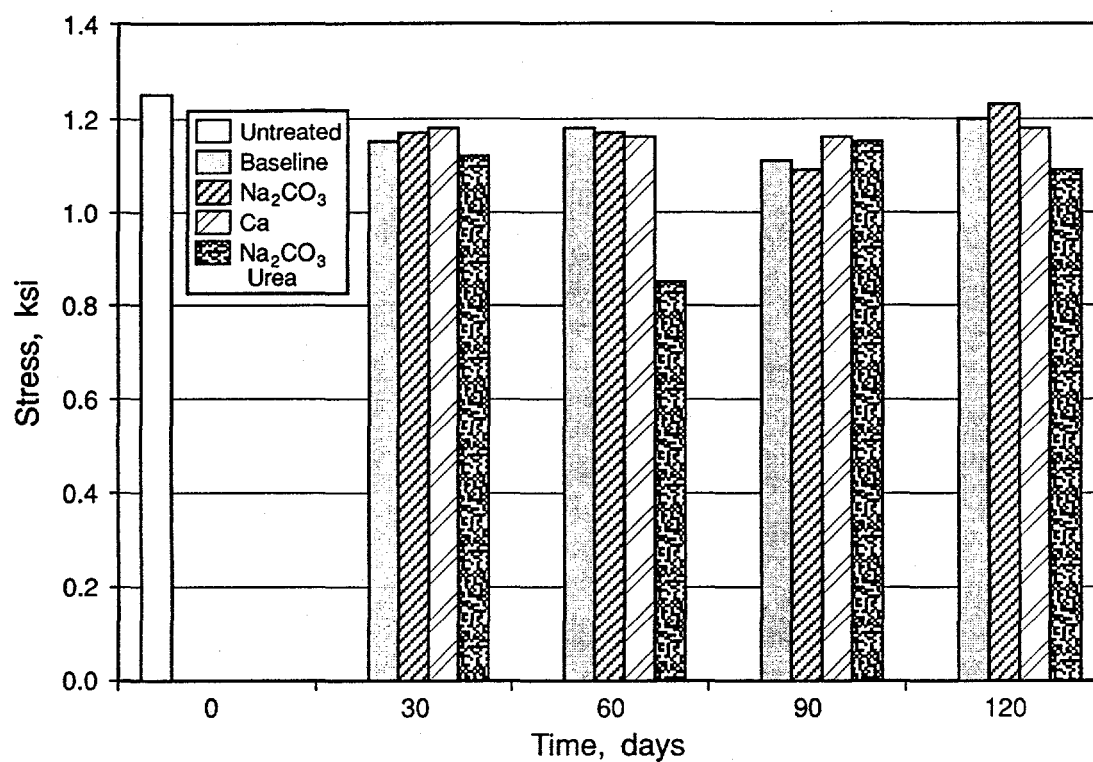


Figure 25. Yield Strength Cross-Grain for VDPE

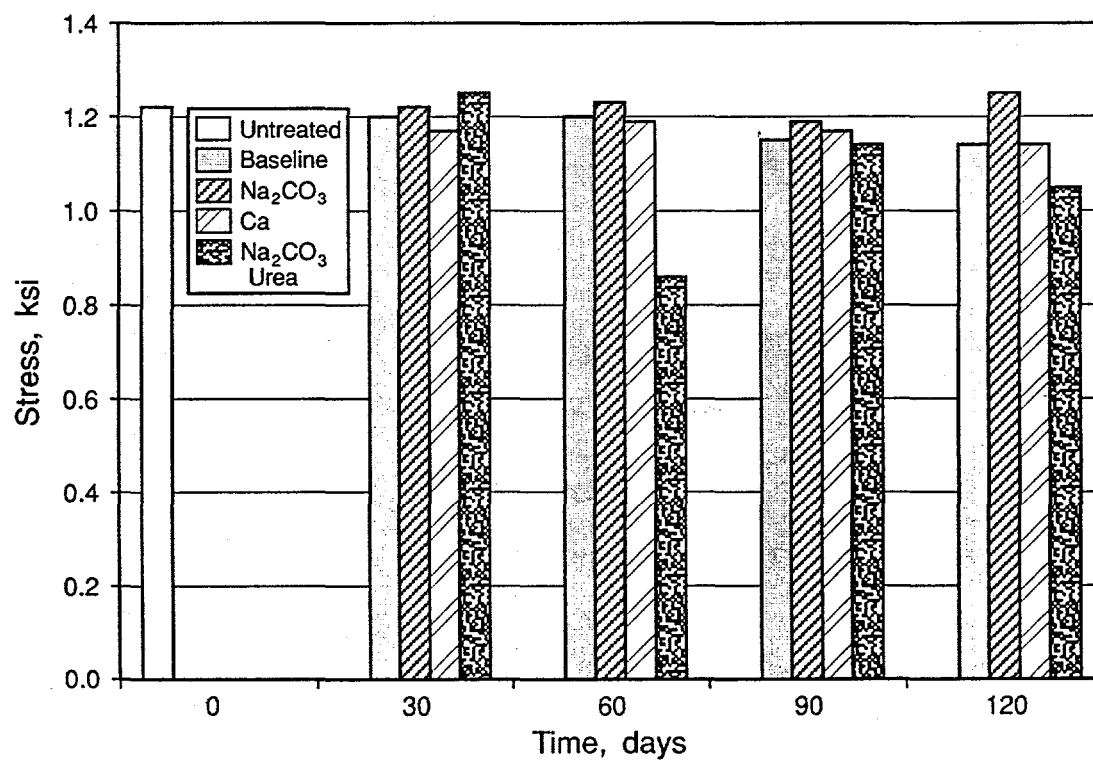


Figure 26. Stress at 100% Elongation With-Grain for VDPE

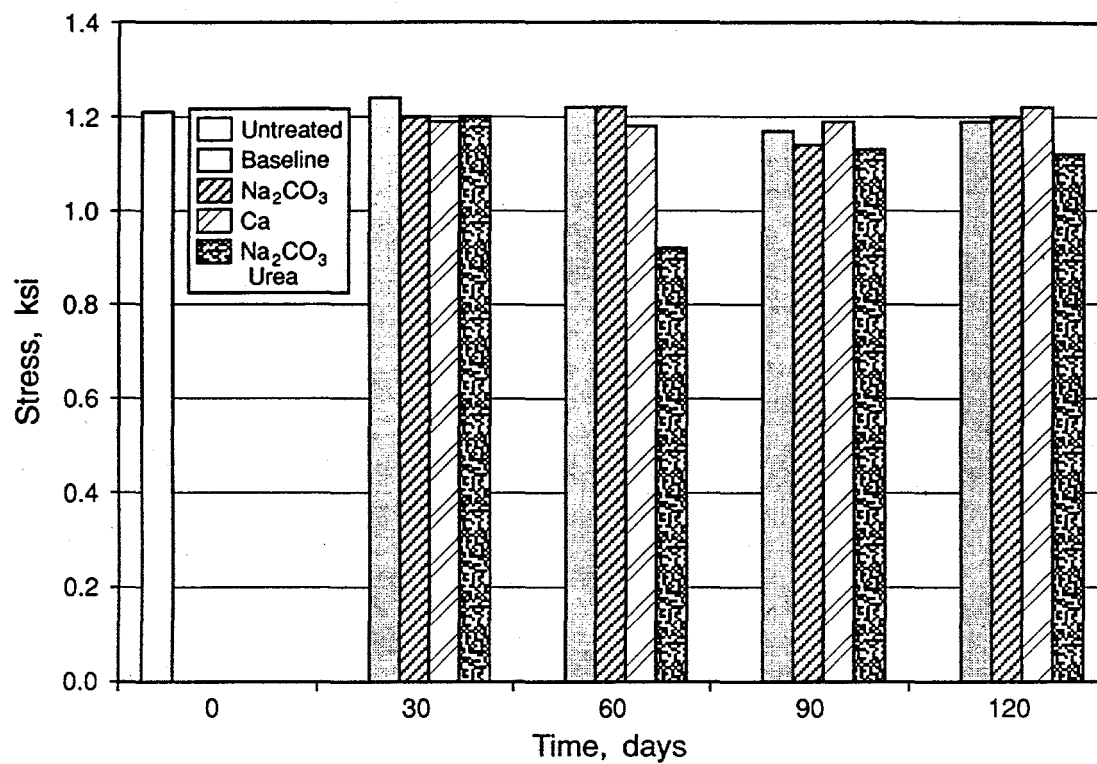


Figure 27. Stress at 100% Elongation Cross-Grain for VDPE

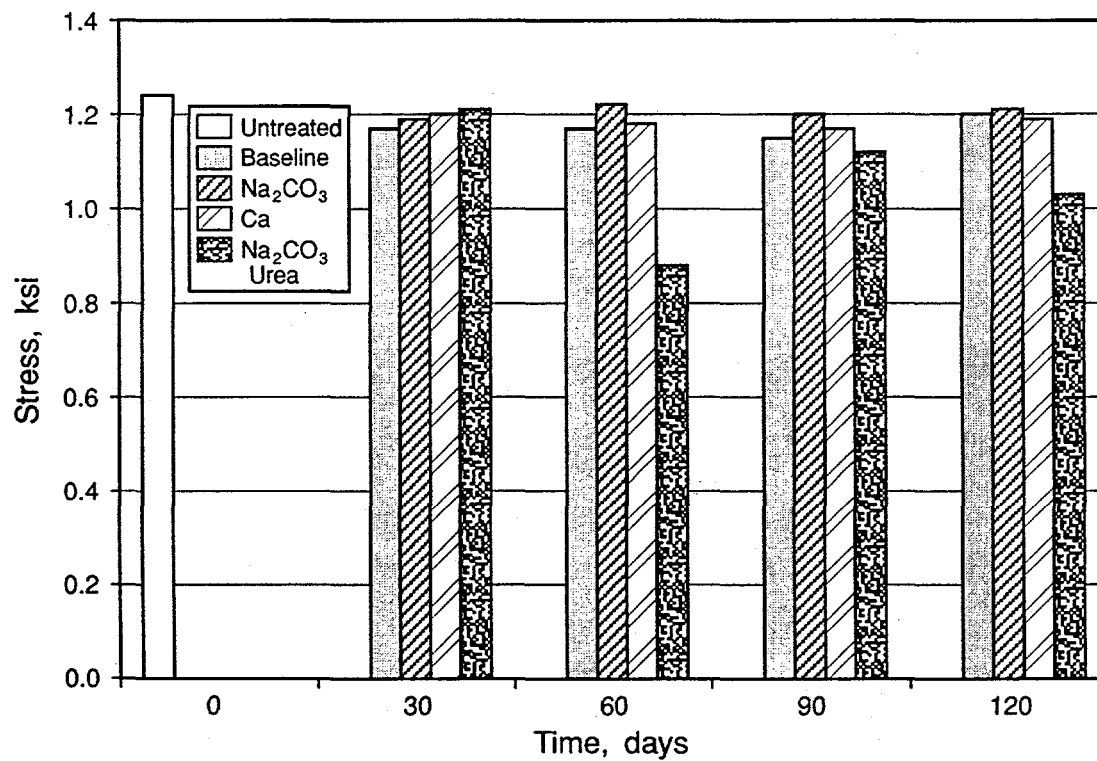


Figure 28. Stress at 200% Elongation With-Grain for VDPE

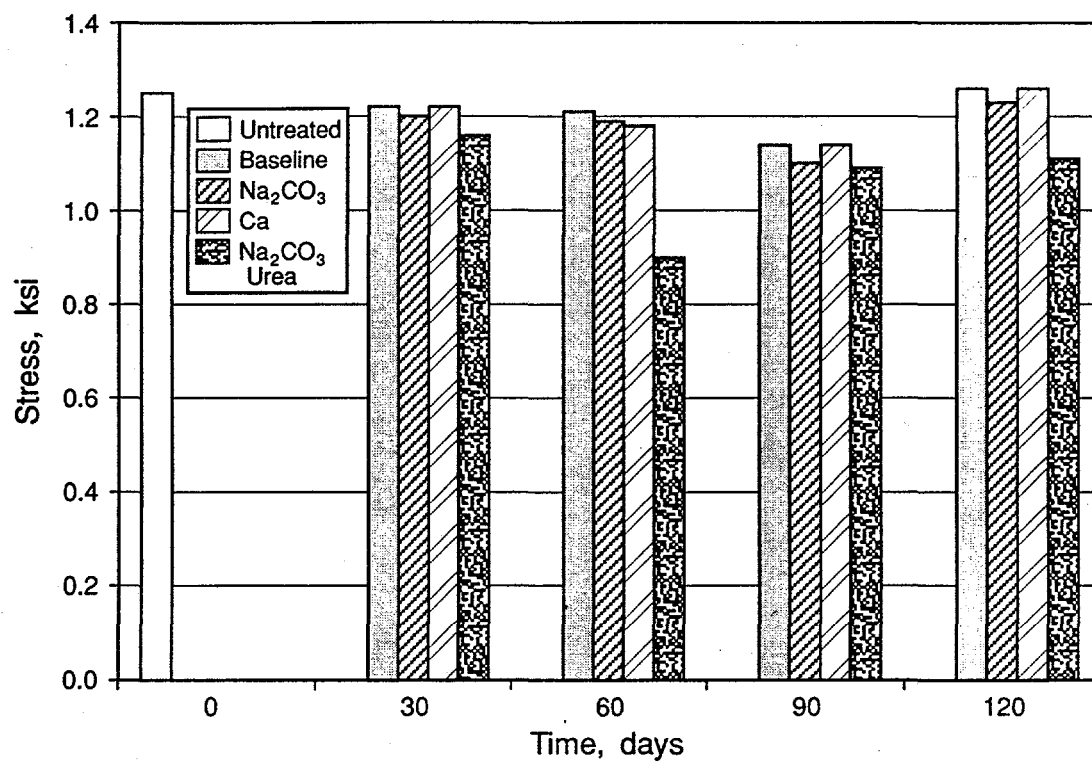


Figure 29. Stress at 200% Elongation Cross-Grain for VDPE

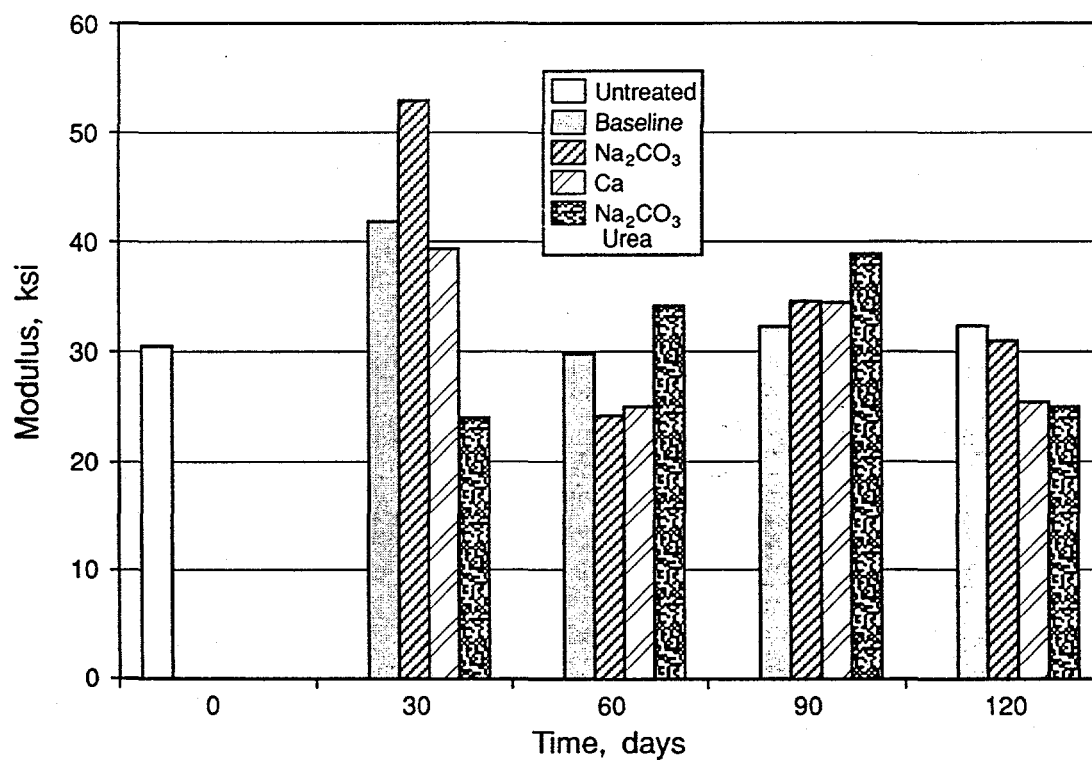


Figure 30. Elastic Modulus With-Grain for VDPE

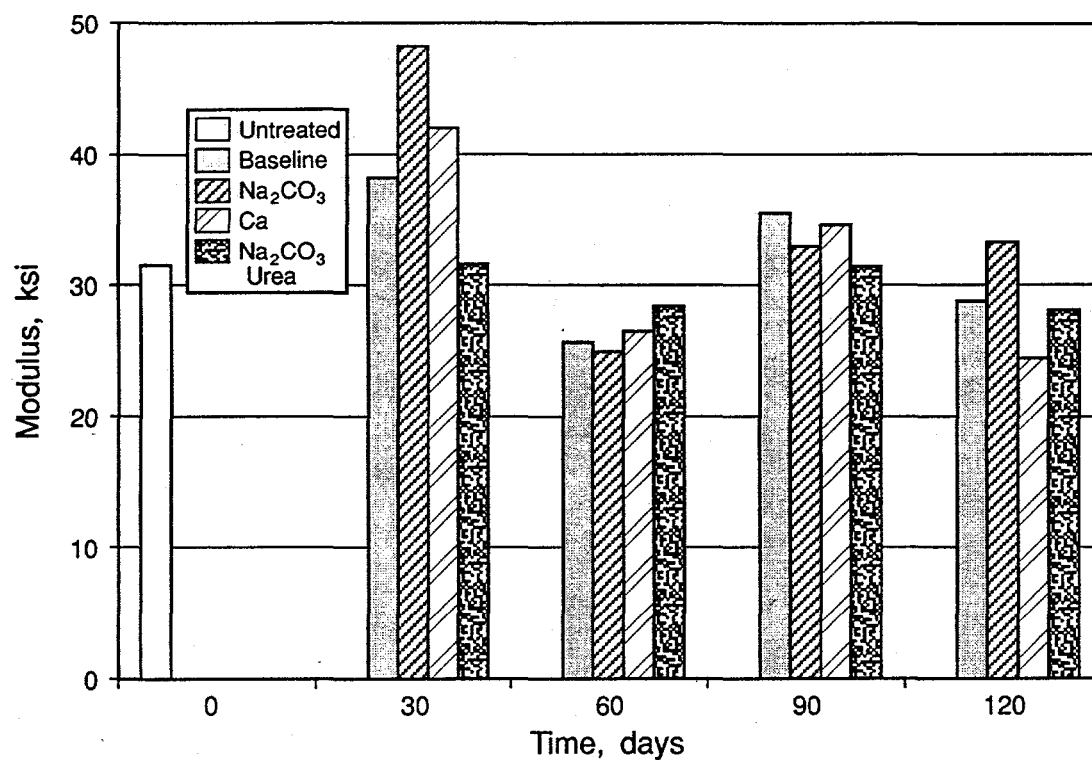


Figure 31. Elastic Modulus Cross-Grain for VDPE

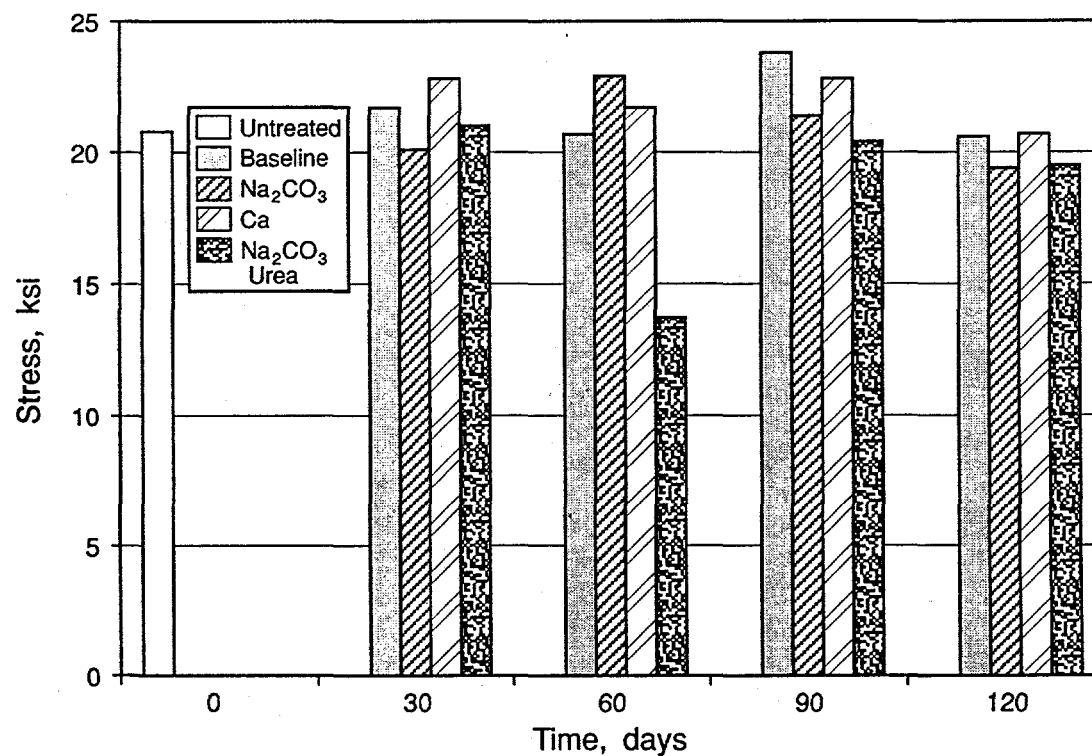


Figure 32. Tear Strength With-Grain for VDPE

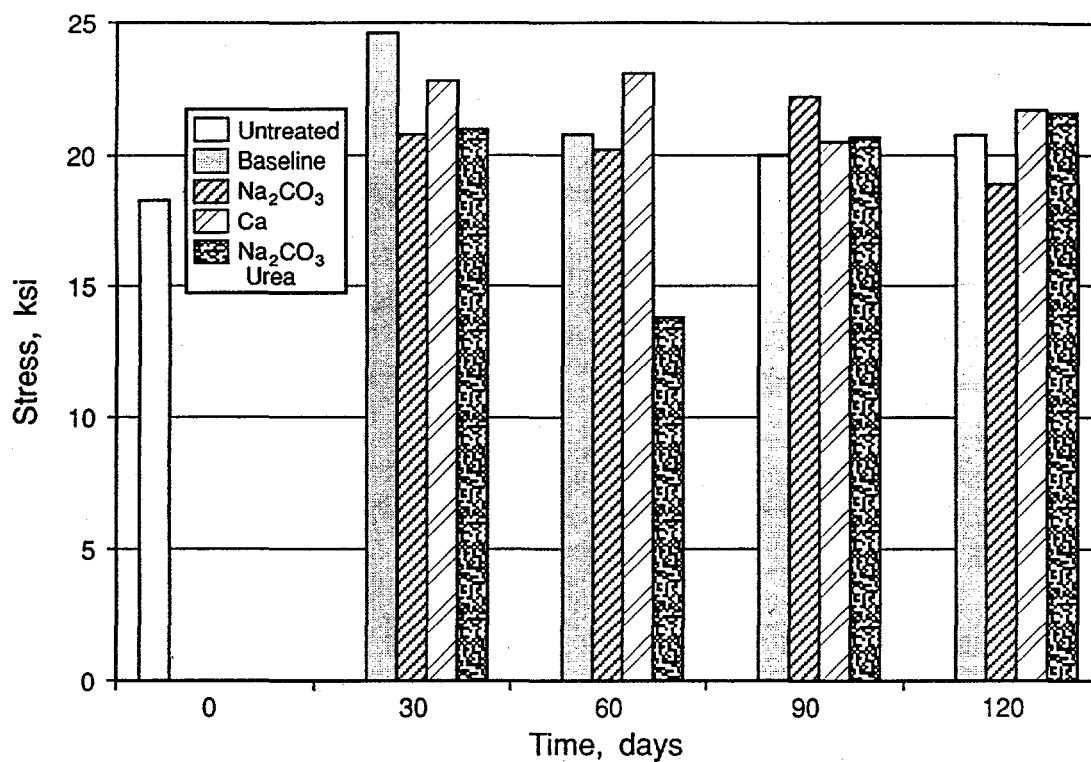


Figure 33. Tear Strength Cross-Grain for VDPE

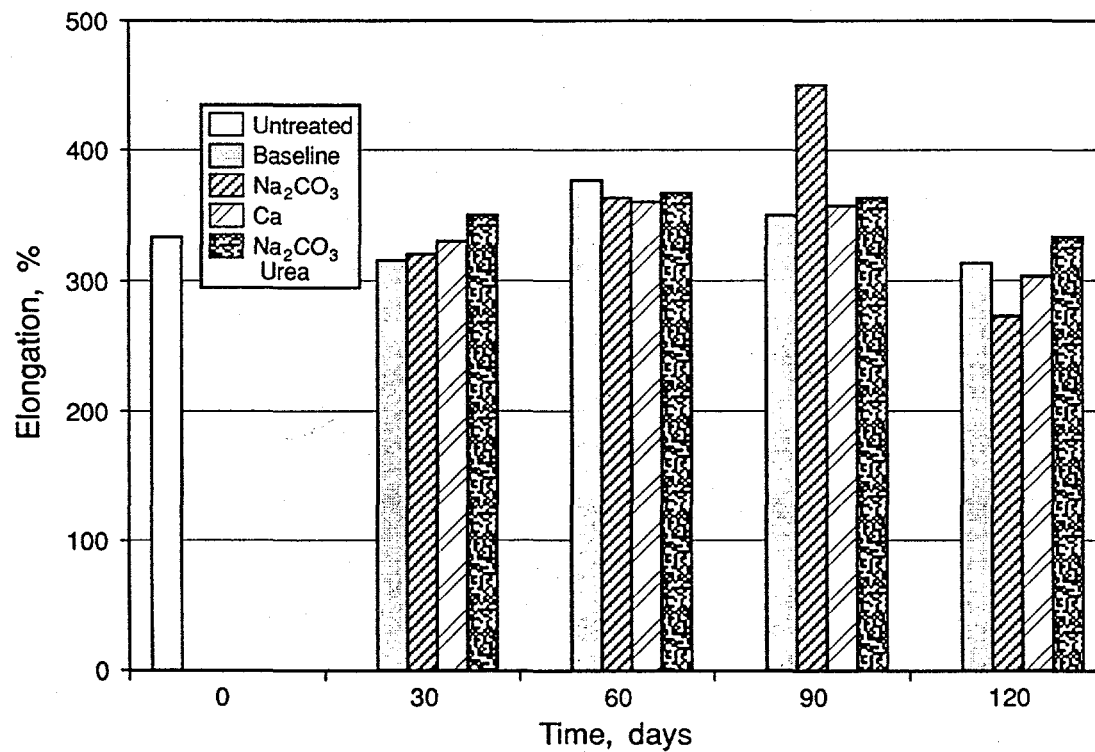


Figure 34. Percent Elongation at Break With-Grain for PVC

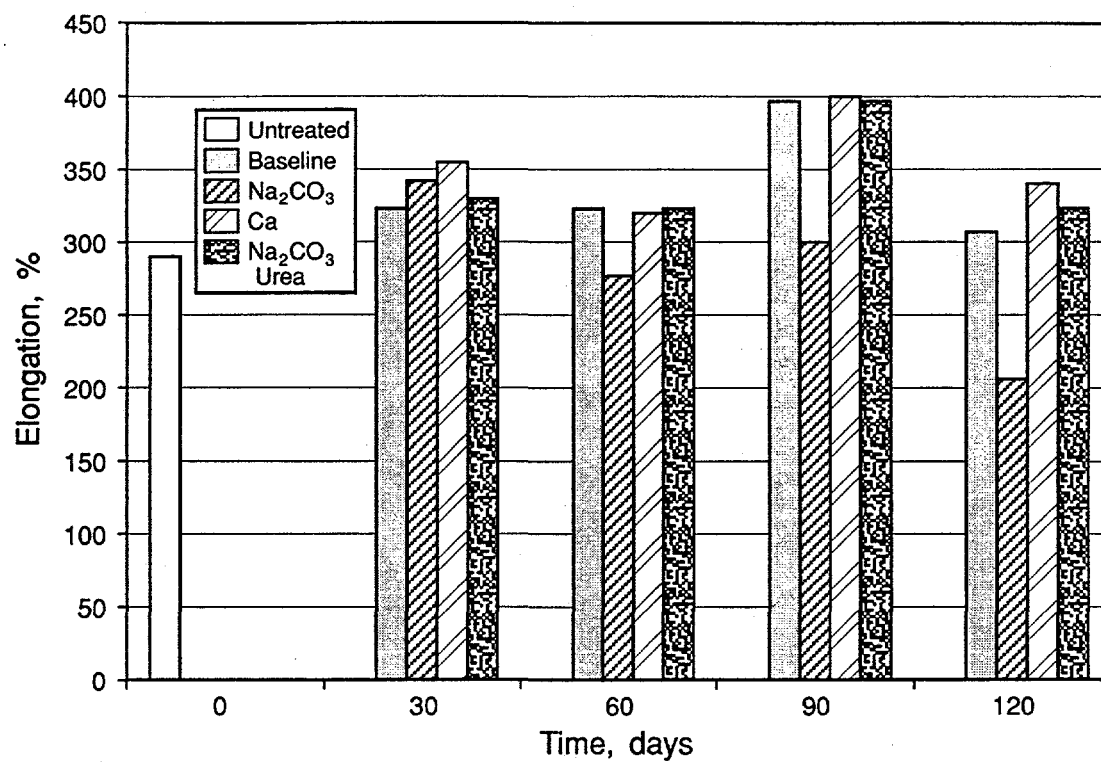


Figure 35. Percent Elongation at Break Cross-Grain for PVC

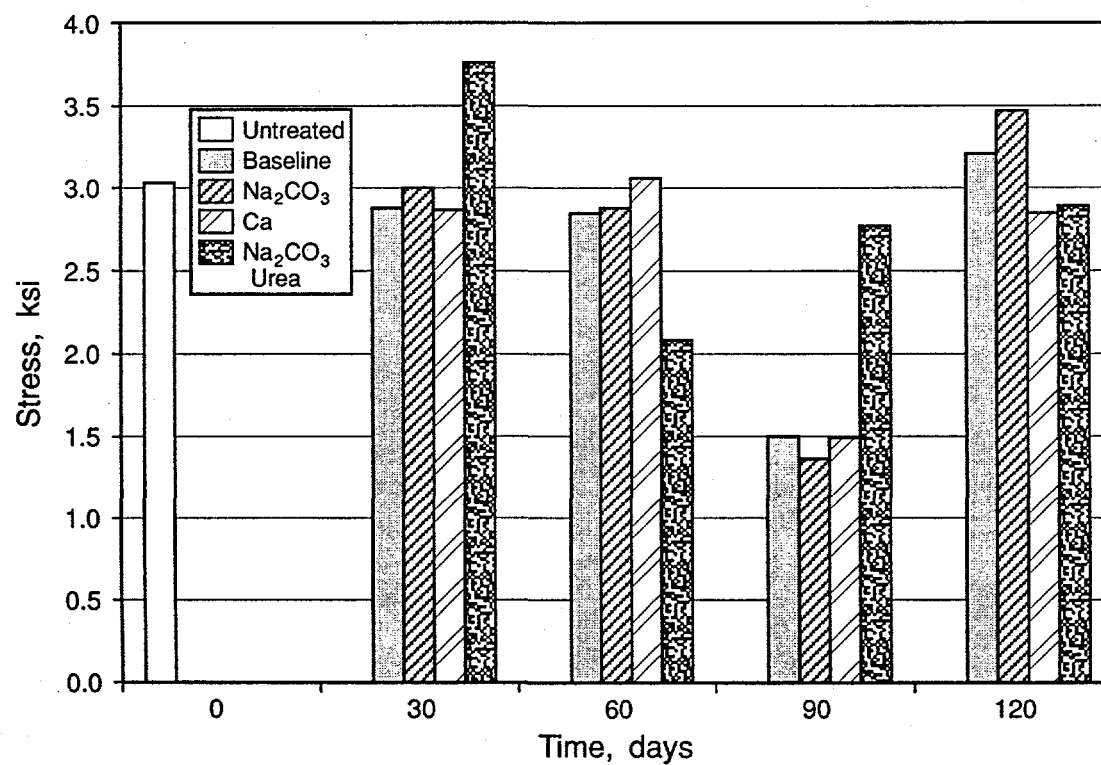


Figure 36. Breaking Strength With-Grain for PVC

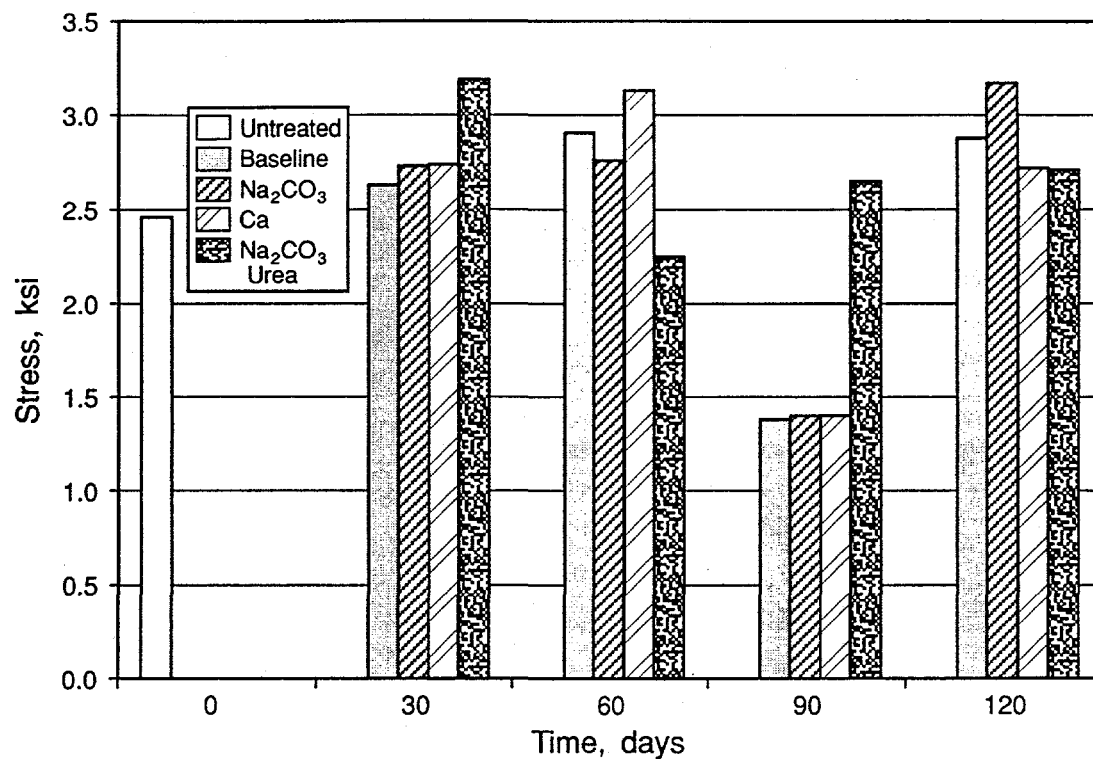


Figure 37. Breaking Strength Cross-Grain for PVC

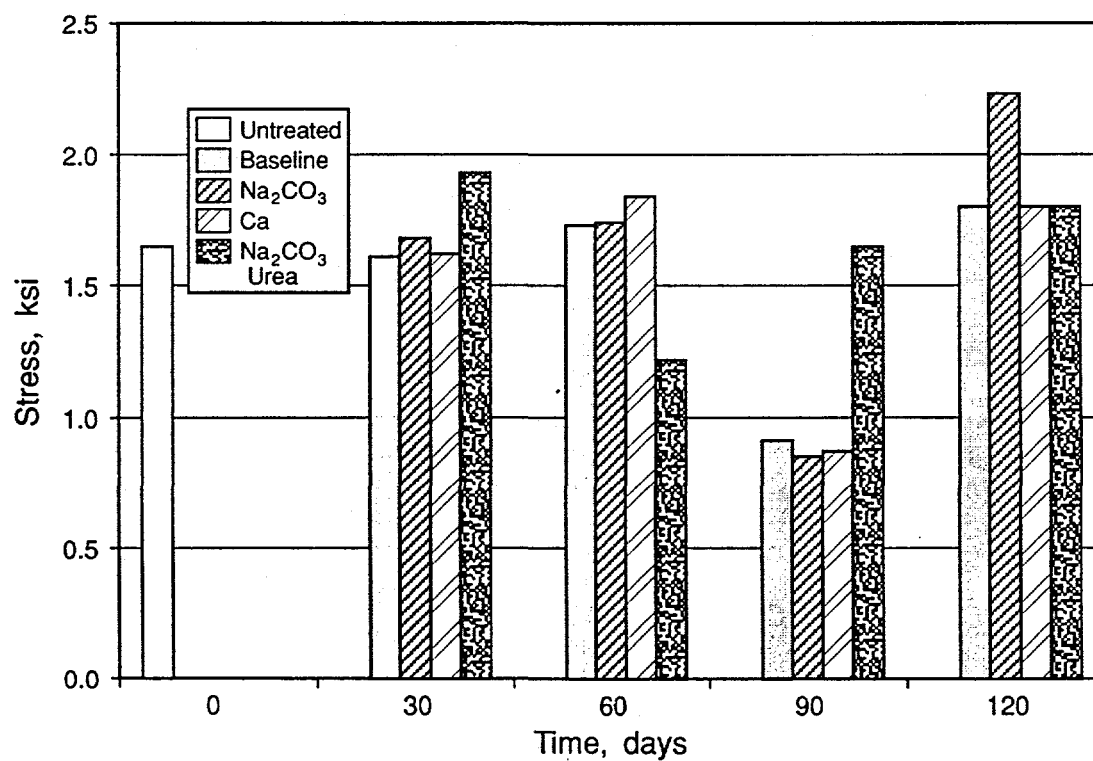


Figure 38. Stress at 100% Elongation With-Grain for PVC

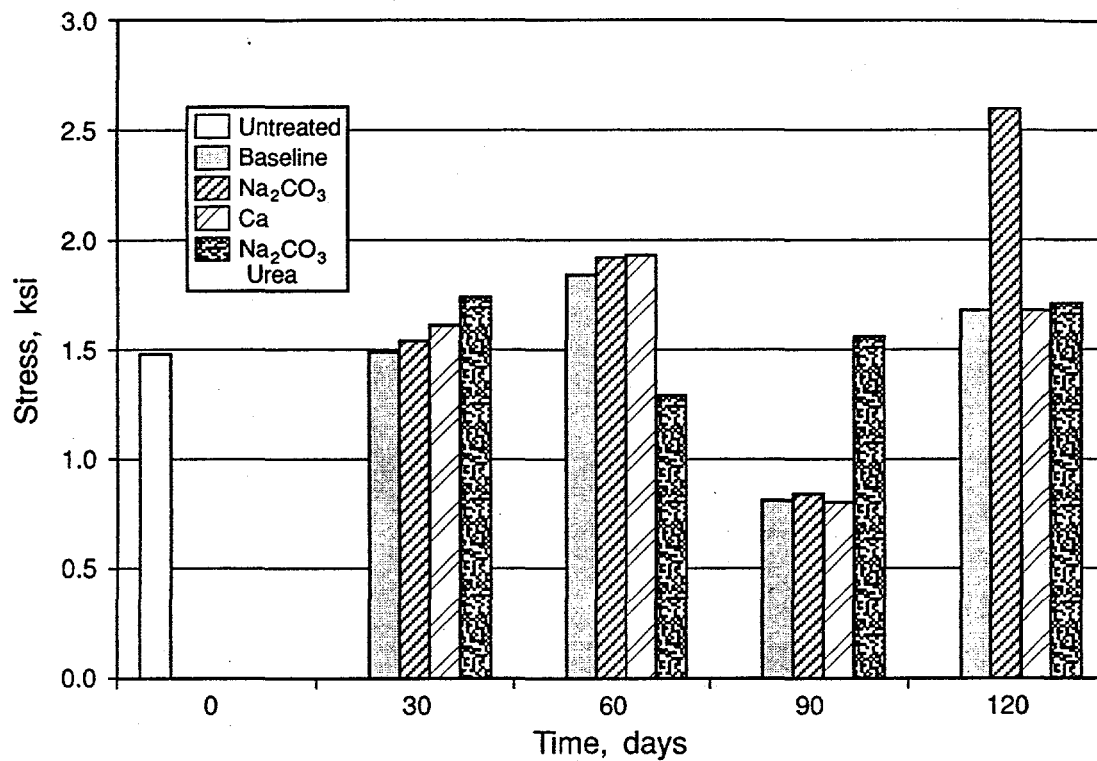


Figure 39. Stress at 100% Elongation Cross-Grain for PVC

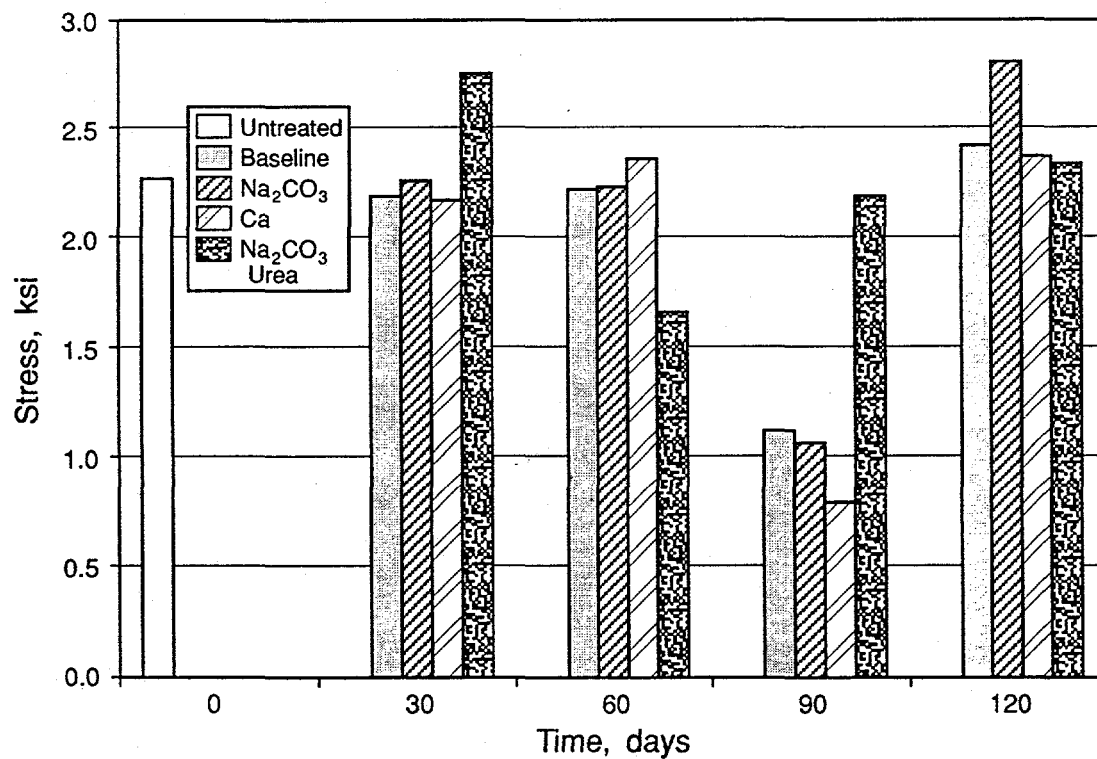


Figure 40. Stress at 200% Elongation With-Grain for PVC

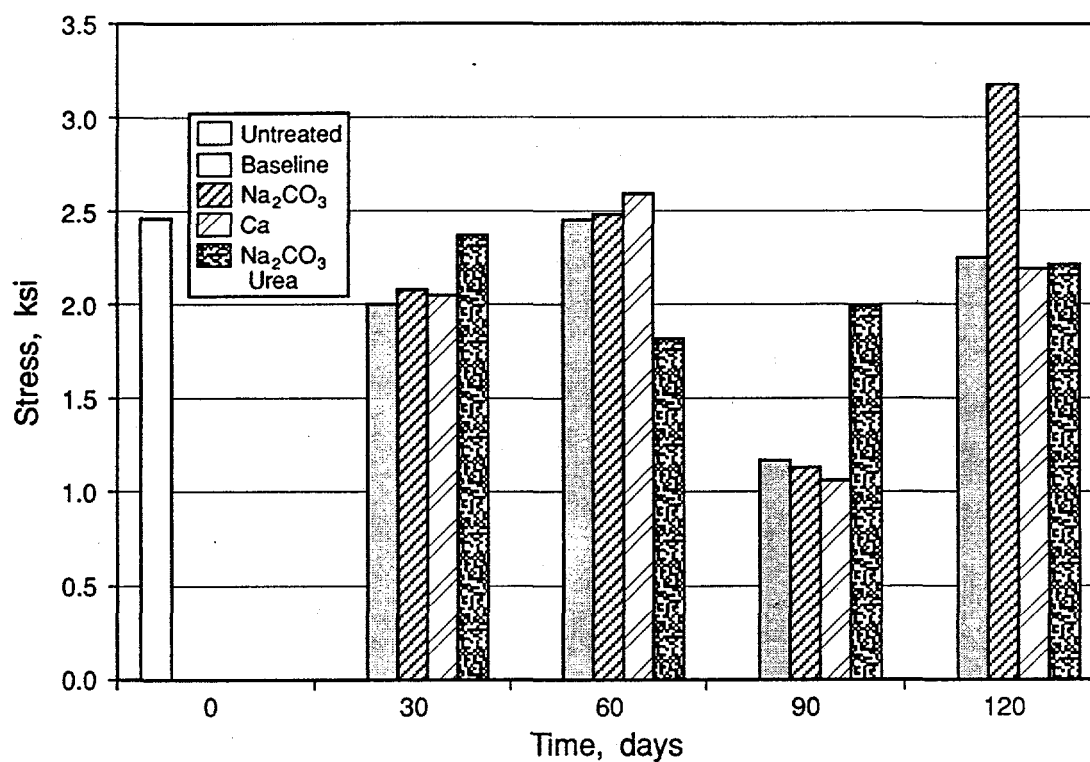


Figure 41. Stress at 200% Elongation Cross-Grain for PVC

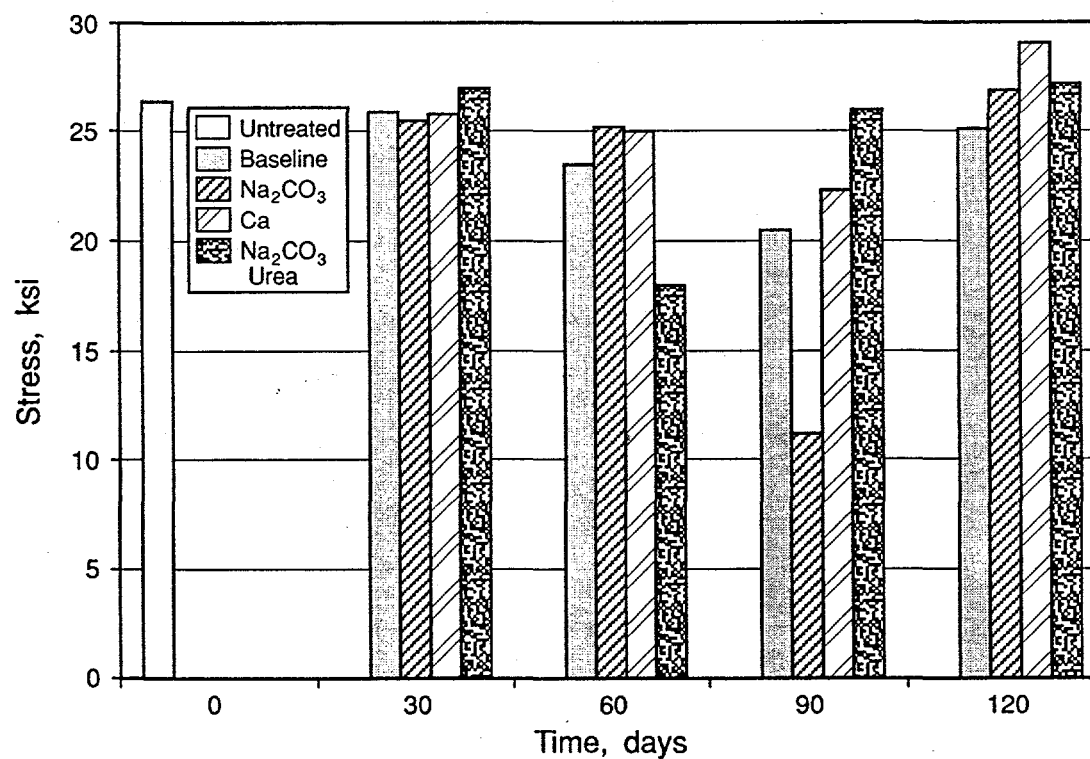


Figure 42. Tear Strength With-Grain for PVC

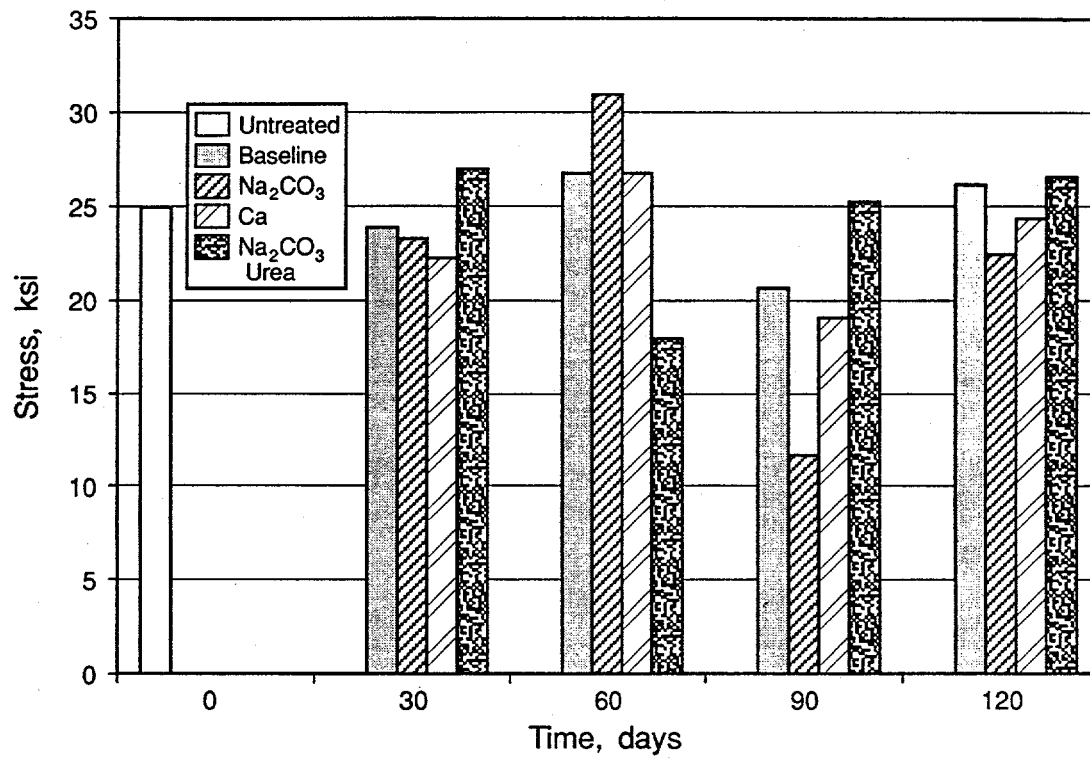


Figure 43. Tear Strength Cross-Grain for PVC

DISCLAIMER

Mention of specific brand names or models of equipment is for information purposes only and does not imply endorsement of any particular brand.

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APPENDIX

DATA SUMMARY FOR PVC
30 Day Conditioning

PROPERTY	UNTREATED		BASELINE		Na ₂ CO ₃		Ca		Na ₂ CO ₃ -UREA	
	AVERAGE	±CV%	AVERAGE	±CV%	AVERAGE	±CV%	AVERAGE	±CV%	AVERAGE	±CV%
WITH GRAIN										
Elongation @ Break (%)	443	6	315	10	320	2	330	1	350	0
Breaking Strength (ksi)	3.06	1	2.88	6	3.00	1	2.87	2	3.76	3
Stress @ 100% Elongation (ksi)	1.80	2	1.61	2	1.68	4	1.62	1	1.93	5
Stress @ 200 % Elongation (ksi)	2.5	2	2.20	1	2.27	2	2.18	1	2.76	2
Tear Strength (lb)	26.4	11	25.9	8	25.5	4	25.8	6	27	2
CROSS GRAIN										
Elongation @ Break (%)	437	6	323	6	342	3	355	2	330	9
Breaking Strength (ksi)	2.76	2	2.63	4	2.73	1	2.74	1	3.19	4
Stress @ 100% Elongation (ksi)	1.69	2	1.49	33	1.54	3	1.61	1	1.74	1
Stress @ 200% Elongation (ksi)	2.25	2	2.00	1	2.08	1	2.05	1	2.37	3
Tear Strength (lb)	25.0	6	23.9	5	23.3	3	22.3	7	27	4
Puncture Force (lb)	89	1	90.0	2	85.9	2	88.5	1.1	92.0	1

DATA SUMMARY FOR PVC
60 Day Conditioning

PROPERTY	BASELINE		Na ₂ CO ₃		Ca		Na ₂ CO ₃ -UREA	
	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV
WITH GRAIN								
Elongation @ Break %	377	4	363	3	360	3	367	8
Breaking Strength ksi	2.85	1	2.88	2	3.06	6	2.08	1
Stress @ 100% Elongation ksi	1.73	2	1.74	0	1.84	5	1.22	2
Stress @ 200 % Elongation ksi	2.23	1	2.24	1	2.37	4	1.67	2
Tear Strength lb	23.5	3	25.2	16	25	9	18	7
CROSS GRAIN								
Elongation @ Break %	323	5	277	4	320	5	323	8
Breaking Strength ksi	2.91	2	2.76	2	3.13	4	2.25	4
Stress @ 100% Elongation ksi	1.84	2	1.92	0	1.93	1	1.29	4
Stress @ 200 % Elongation ksi	2.45	1	2.48	1	2.59	0	1.82	3
Tear Strength lb	26.8	11	31	19	26.8	14	18	7
Puncture Force lb	85.5	1	86.4	0	88.2	1	86	0

DATA SUMMARY FOR PVC
90 Day Conditioning

PROPERTY	BASELINE		Na ₂ CO ₃		Ca		Na ₂ CO ₃ -UREA	
	AVERAGE	±CV%	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV
WITH GRAIN								
Elongation @ Break %	350	0	450	22	357	3	363	6
Breaking Strength ksi	1.50	3	1.36	2	1.49	0	2.77	1
Stress @ 100% Elongation ksi	0.91	2	0.85	5	0.87	2	1.65	1
Stress @ 200 % Elongation ksi	1.13	0.9	1.07	2	1.14	3	2.20	2
Tear Strength lb	20.5	2	11.2	2	22.3	2	26	5
CROSS GRAIN								
Elongation @ Break %	397	1	300	17	400	0	377	3
Breaking Strength ksi	1.38	2	1.40	13	1.40	2	2.65	1
Stress @ 100% Elongation ksi	0.81	1	0.84	5	0.80	2	1.56	1
Stress @ 200 % Elongation ksi	1.17	9	1.13	3	1.06	3	1.99	0
Tear Strength lb	20.7	3	11.7	5	19.1	4	25.3	8
Puncture Force lb	83	1	42.8	2	84	1	91.4	1

DATA SUMMARY FOR PVC
120 Day Conditioning

PROPERTY	BASELINE		Na ₂ CO ₃		Ca		Na ₂ CO ₃ -UREA	
	AVERAGE	±CV%	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV
WITH GRAIN								
Elongation @ Break %	313	3	273	17	303	12	333	17
Breaking Strength ksi	3.21	2	3.47	17	2.85	3	2.89	1
Stress @ 100% Elongation ksi	1.80	0	2.23	8	1.80	0	1.80	3
Stress @ 200 % Elongation ksi	2.43	0	2.81	2	2.38	1	2.35	2
Tear Strength lb	25.1	5	26.9	8	29.1	7	27.2	9
CROSS GRAIN								
Elongation @ Break %	307	4	206	5	340	5	323	5
Breaking Strength ksi	2.88	3	3.17	5	2.72	1	2.71	1
Stress @ 100% Elongation ksi	1.68	2	2.60	6	1.68	1	1.71	1
Stress @ 200 % Elongation ksi	2.25	2	3.17	5	2.19	2	2.21	1
Tear Strength lb	26.2	16	22.5	0	24.4	9	26.6	5
Puncture Force lb	101	0	90	1	103	1	100	1

DATA SUMMARY FOR HDPE
30 Day Conditioning

PROPERTY	UNTREATED			BASELINE			Na ₂ CO ₃			Ca			Na ₂ CO ₃ -UREA		
	AVERAGE	±CV%		AVERAGE	±CV%		AVERAGE	±CV%		AVERAGE	±CV%		AVERAGE	±CV%	
WITH GRAIN															
Elongation @ Yield (%)	13	8		15.7	13		12.7	4.5		13.3	31		19	6	
Elongation @ Break (%)	292	65		548	0		395	42		362	66		660	2	
Yield Strength (ksi)	2.95	3		2.83	2		2.83	2.1		2.69	5		1.17	1	
Breaking Strength (ksi)	2.1	7		2.78	6		2.05	5.7		2.33	14		1.20	11	
Stress @ 100% Elongation (ksi)	1.62	44		2.11	4		1.9	1.6		2.14 ¹	2		0.79	1	
Stress @ 200 % Elongation (ksi)	2.06 ¹	2		2.20	7		1.85	11		2.17 ¹	4		0.80	1	
Elastic Modulus (ksi)	114	9		119	12		169	15.5		125	11		86.3	23	
Tear Strength (lb)	47.2	3		47.7	4		48.4	3		49.9	4		46	4	
CROSS GRAIN															
Elongation @ Yield (%)	14.3	4		14.0	0		18.3	42		18.3	19		18	8	
Elongation @ Break (%)	478	14		627	2		377	58		243	110		620	5	
Yield Strength (ksi)	2.8	3		2.98	1		2.76	3		2.89	6		1.11	1	
Breaking Strength (ksi)	2.36	15		2.92	3		2.16	4		2.27 ¹	10		1.22	6	
Stress @ 100% Elongation (ksi)	2.05	1		1.97	2		2.06	2		1.92 ²			0.80	1	
Stress @ 200% Elongation (ksi)	2.10	2		1.99	2		2.05 ¹	3		1.92 ²			0.82	1	
Elastic Modulus (ksi)	101	9		125	2		146	20		126	8		77.9	--	
Tear Strength (lb)	49.7	3		48.1	2		50.5	5		48.7	6		47	8	
Puncture Force (lb)	135	2		133	1		136	2		134	1		140	1	

DATA SUMMARY FOR HDPE
60 Day Conditioning

PROPERTY	BASELINE		Na ₂ CO ₃		Ca		Na ₂ CO ₃ -UREA	
	AVERAGE	±CV%	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV
WITH GRAIN								
Elongation @ Yield %	16.3	7	15.3	10	14.3	4	20.3	3
Elongation @ Break %	242	95	350	45	250	76	460	40
Yield Strength ksi	2.75	4	2.61	2	2.75	0	2.03	1
Breaking Strength ksi	2.00	4	2.03	17	2.08	2	1.50	6
Stress @ 100% Elongation ksi.	1.97	2	1.80	1	2.07	2	1.36	1
Stress @ 200 % Elongation ksi	1.95*		1.84	2	2.06*		1.39	1
Elastic Modulus ksi	86.6	0	92.2	0	84	5	78.4	36
Tear Strength lb	46.1	4	45.5	4	46.1	3	33.5	4
CROSS GRAIN								
Elongation @ Yield %	13.0	15	13.7	4	15.0	7	20	3
Elongation @ Break %	393	63	407	45	410	49	303	35
Yield Strength ksi	2.93	2	2.48	3	2.8	4	1.98	2
Breaking Strength ksi	2.18	14	2.02	8	2.04	11	1.51	3
Stress @ 100% Elongation ksi	1.85	12	1.88	2	1.93	7	1.45	0
Stress @ 200 % Elongation ksi	2.06	2	1.47	56	1.98	2	1.48	1
Elastic Modulus ksi	88.6	3	85.1	5	88.2	7	93.9	8
Tear Strength lb	44.2	4	47.2	7	45.3	6	34.6	2
Puncture Force lb	133	6	129	2	138	1	131	0

* Only one data point available, therefore no average or CV.

DATA SUMMARY FOR HDPE
90 Day Conditioning

PROPERTY	BASELINE		Na ₂ CO ₃		Ca		Na ₂ CO ₃ -UREA	
	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV
WITH GRAIN								
Elongation @ Yield %	17.7	12	22	20	30	47	19.7	3
Elongation @ Break %	587	4	640	9	540	13	435	66
Yield Strength ksi	2.88	1	2.92	1	2.78	3	2.76	2
Breaking Strength ksi	2.82	7	2.93	4	2.38	17	2.27	7
Stress @ 100% Elongation ksi	1.94	1	1.86	0	1.84	3	1.80	0
Stress @ 200 % Elongation ksi	2.01	2	1.92	2	1.96	1	1.85	1
Elastic Modulus ksi	88.1	2	93.9	5	125.7	8	104.8	1
Tear Strength lb	44.2	1	45.3	8	45.5	9	49.8	4
CROSS GRAIN								
Elongation @ Yield %	20	0	19.3	5	26	16	19.3	3
Elongation @ Break %	503	18	562	7	568	1	463	47
Yield Strength ksi	2.80	1	2.79	0	2.77	1	2.65	0
Breaking Strength ksi	2.44	16	2.84	1	2.61	8	2.44	8
Stress @ 100% Elongation ksi	2.03	0	1.99	1	2.03	1	1.92	2
Stress @ 200 % Elongation ksi	2.06	1	2.05	1	2.05	0	1.98	
Elastic Modulus ksi	96	1	90.6	4	84	0	96.8	5
Tear Strength lb	47.3	4	47.3	1	46.6	4	52.3	17
Puncture Force lb	132.1	0	132.7	1	>121.2	>7	128	0

DATA SUMMARY FOR HDPE
120 Day Conditioning

PROPERTY	BASELINE		Na ₂ CO ₃		Ca		Na ₂ CO ₃ -UREA	
	AVERAGE	±CV%	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV
WITH GRAIN								
Elongation @ Yield %	18.3	6	19.3	6	20	0	19.3	6
Elongation @ Break %	557	7	603	8	380	54	427	51
Yield Strength ksi	2.79	0	2.73	3	2.82	2	2.69	4
Breaking Strength ksi	2.52	16	2.66	15	1.99	10	1.97	10
Stress @ 100% Elongation ksi	1.98	1	1.95	5	1.85	3	1.77	2
Stress @ 200 % Elongation ksi	2.00	1	1.72	23	1.91	0	1.83	2
Elastic Modulus ksi	85.1	1	99.3	2	101	1	96.8	0
Tear Strength lb	42.7	3	51.3	5	45.5	11	43	4
CROSS GRAIN								
Elongation @ Yield %	19.3	5	19	5	20.3	3	20	0
Elongation @ Break %	543	16	617	5	423	26	327	75
Yield Strength ksi	2.87	1	2.8	3	2.70	1	2.70	4
Breaking Strength ksi	2.30	17	2.73	11	2.00	1	1.98	4
Stress @ 100% Elongation ksi	1.83	3	1.83	5	1.93	1	1.92	0
Stress @ 200 % Elongation ksi	1.88	2	1.87	5	1.98	1	1.95	0
Elastic Modulus ksi	95	2	101.2	1	94.7	2	95.6	4
Tear Strength lb	44.2	9	42.6	7	50.9	5	47.5	11
Puncture Force lb	137	0	133	0	144	0	145	0

DATA SUMMARY FOR VDPE
30 Day Conditioning

PROPERTY	UNTREATED		BASELINE		Na ₂ CO ₃		Ca		Na ₂ CO ₃ -UREA	
	AVERAGE	±CV%	AVERAGE	±CV%	AVERAGE	±CV%	AVERAGE	±CV%	AVERAGE	±CV%
WITH GRAIN										
Elongation @ Yield (%)	18	10	15	7	15.7	4	14.0	12	20	0
Elongation @ Break (%)	490	40	>630		>630	1	>622		660	2
Yield Strength (ksi)	1.22	3	1.16	3	1.18	2	1.18	3	1.13	0
Breaking Strength (ksi)	2.03	34	>2.82		>2.95		>2.72		3.08	1
Stress @ 100% Elongation (ksi)	1.22	3	1.20	2	1.22	2	1.17	2	1.25	1
Stress @ 200 % Elongation (ksi)	1.24	3	1.17	1	1.19	2	1.20	2	1.21	0
Elastic Modulus (ksi)	30.5	2	41.8	3	52.9	1	39.4	13	24.0	19
Tear Strength (lb)	20.8	7	21.7	4	20.1	3	22.8	8	21	5
CROSS GRAIN										
Elongation @ Yield (%)	16.0	6	17.0	10	19.7	15	15.3	4	19	7
Elongation @ Break (%)	>570		>615		>645	3	>625		677	2
Yield Strength (ksi)	1.25	1	1.15	0	1.17	3	1.18	2	1.12	4
Breaking Strength (ksi)	>3.29		>2.84		>2.92		>2.76		2.89	2
Stress @ 100% Elongation (ksi)	1.21	0	1.24	2	1.20	2	1.19	1	1.20	2
Stress @ 200% Elongation (ksi)	1.25	3	1.22	0	1.20	2	1.22	1	1.16	3
Elastic Modulus (ksi)	31.5	7	38.2	8	48.2	7	42.0	1	31.6	9
Tear Strength (lb)	18.3	2	24.6	11	20.8	3	22.8	6	21	8
Puncture Force (lb)	58.0	2	62.7	0	60.3	4	62.7	1	67	1

* Only one data point available, therefore no average or CV.

DATA SUMMARY FOR VDPE

60 Day Conditioning

PROPERTY	BASELINE		Na ₂ CO ₃		Ca		Na ₂ CO ₃ -UREA	
	AVERAGE	±CV%	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV
WITH GRAIN								
Elongation @ Yield %	17.7	3	17.0	6	15.7	4	19	5
Elongation @ Break %	>635*		611	2	>615*		>670	>9
Yield Strength ksi	1.18	3	1.19	3	1.18	0	0.84	0
Breaking Strength ksi	>2.60*		2.63	4	>2.55*		>2.1	15
Stress @ 100% Elongation ksi	1.20	2	1.23	2	1.19	1	0.86	1
Stress @ 200 % Elongation ksi	1.17	3	1.22	3	1.18	0	0.88	0
Elastic Modulus ksi	29.8	10	24.2	13	25.0	24	34.2	7
Tear Strength lb	20.7	2	22.9	5	21.7	8	13.7	15
CROSS GRAIN								
Elongation @ Yield %	17.3	9	19.3	3	17.3	3	18	14
Elongation @ Break %	>620*		588	6	>620*		670	2
Yield Strength ksi	1.18	1	1.17	1	1.16	1	0.85	1
Breaking Strength ksi	>2.69*		2.46	11	>2.63*		>2.3	3
Stress @ 100% Elongation ksi	1.22	1	1.22	2	1.18	2	0.92	1
Stress @ 200 % Elongation ksi	1.21	1	1.19	1	1.18	2	0.90	1
Elastic Modulus ksi	25.7	8	25.0	18	26.5	5	28.4	15
Tear Strength lb	20.8	1	20.2	4	23.1	6	13.8	6
Puncture Force lb	60.1	0	62.4	0	63.8	3	49	17

* Only one data point available, therefore no average or CV.

DATA SUMMARY FOR VDPE
90 Day Conditioning

PROPERTY	BASELINE		Na ₂ CO ₃		Ca		Na ₂ CO ₃ -UREA	
	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV
WITH GRAIN								
Elongation @ Yield %	15.7	6	32	19	20.3	6	20	5
Elongation @ Break %	>590*		>673	>6	>615	0	>653	1
Yield Strength ksi	1.13	2	1.16	3	1.17	1	1.16	3
Breaking Strength ksi	>2.49*		2.7	11	>2.48*		2.54	2
Stress @ 100% Elongation ksi	1.15	0	1.19	2	1.17	1	1.14	3
Stress @ 200 % Elongation ksi	1.15	0	1.20	4	1.17	3	1.12	2
Elastic Modulus ksi	32.3	10	34.6	16	34.5	1	38.9	5
Tear Strength lb	23.8	13	21.4	3	22.8	8	20.4	8
CROSS GRAIN								
Elongation @ Yield %	18	4	28	3	18.3	3	17.3	3
Elongation @ Break %	>590*		>617	>14	>615*		>647	1
Yield Strength ksi	1.11	0	1.09	5	1.16	3	1.15	3
Breaking Strength ksi	>2.50*		2.08	24	>2.40*		2.64	1
Stress @ 100% Elongation ksi	1.17	1	1.14	0	1.19	3	1.13	3
Stress @ 200 % Elongation ksi	1.14	1	1.10	4	1.14	3	1.09	2
Elastic Modulus ksi	35.5	8	33	1	34.6	5	31.4	9
Tear Strength lb	20	0	22.2	5	20.5	3	20.7	14
Puncture Force lb	59	2	59	1	58	2	67.8	1

* Only one data point available, therefore no average or CV.

DATA SUMMARY FOR VDPE
120 Day Conditioning

PROPERTY	BASELINE		Na ₂ CO ₃		Ca		Na ₂ CO ₃ - UREA	
	AVERAGE	±CV%	AVERAGE	±%CV	AVERAGE	±%CV	AVERAGE	±%CV
WITH GRAIN								
Elongation @ Yield %	18.7	12	21.7	13	19.7	3	18.7	6
Elongation @ Break %	>710	1	>510	47	>710	0	>640	3
Yield Strength ksi	1.14	3	1.26	3	1.19	6	1.01	7
Breaking Strength ksi	3.20	3	>2.3	61	3.10	4	2.32	3
Stress @ 100% Elongation ksi	1.14	3	1.25	3	1.14	3	1.05	4
Stress @ 200 % Elongation ksi	1.20	2	1.21	15	1.19	3	1.03	5
Elastic Modulus ksi	32.4	6	31.0	14	25.4	11	25.0	5
Tear Strength lb	20.6	2	19.4	2	20.7	5	19.5	2
CROSS GRAIN								
Elongation @ Yield %	20.3	3	20	0	19	9	20	0
Elongation @ Break %	>673	2	>693	4	>680	3	>647	1
Yield Strength ksi	1.20	4	1.23	6	1.18	5	1.09	8
Breaking Strength ksi	3.17	2	>3.16	2	3.17	3	>2.38	1
Stress @ 100% Elongation ksi	1.19	3	1.20	4	1.22	2	1.12	4
Stress @ 200 % Elongation ksi	1.26	3	1.23	7	1.26	3	1.11	8
Elastic Modulus ksi	28.8	2	33.3	7	24.5	42	28.1	4
Tear Strength lb	20.8	1	18.9	2	21.7	8	21.6	3
Puncture Force lb	70	2	58.2	2	70	2	57	1